ARTIFICIAL SUNLIGHT

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Artificial Sunlight

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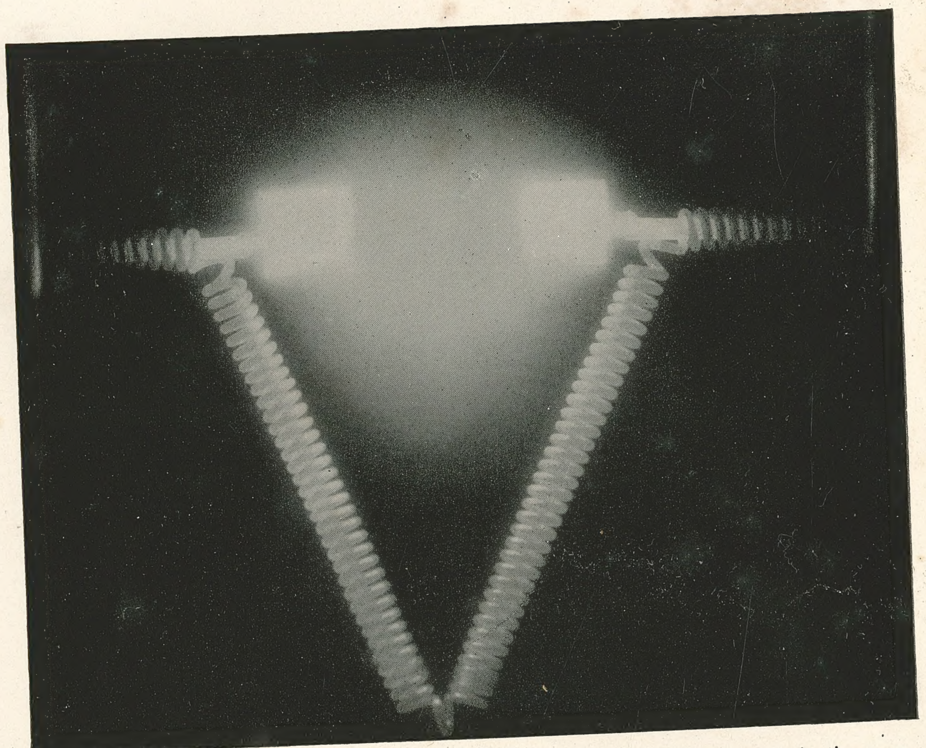

FRONTISPIECE. A new light-source is such a rare event that it deserves distinctive mention. The Sunlight (Type S-1) lamp, a recent development of the General Electric Company, consists of a mercury arc between tungsten electrodes and a tungsten filament in parallel with it. The source is enclosed in a bulb which transmits ultraviolet radiation longer than λ2800.

ARTIFICIAL SUNLIGHT

COMBINING RADIATION FOR HEALTH WITH LIGHT FOR VISION

BY

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PREFACE

Radiant energy has to its credit notable achievements in the cure of illness; and midsummer sunlight is entitled to a prominent place in this respect. Besides this field, which should be the exclusive territory of the medical profession, there is the important aspect of health-maintenance. It is the responsibility of every art, science, and individual in a position to do so, to contribute to the maintenance of the health of human beings. Summer sunlight is recognized as an adjuvant, a preventive of illness, a factor in the maintenance of health. The development of safe and effective substitutes for midsummer sunlight has been a natural objective of light-production. Artificial lighting includes among its opportunities and responsibilities in the indoor world, the provision of the equivalent of that powerful environmental factor under which human beings evolved outdoors. Many gaps exist in our knowledge of the biological effects of radiation, but the foundation appears to be sufficiently established to warrant the inauguration of a new era of dual-purpose lighting, including radiant energy for health as well as light for vision.

In this treatise, effects of radiant energy have been coordinated with the physics of the subject—a combination which is often incomplete in biological researches and in therapeutic practice. For this reason it is hoped that the data and discussions in these chapters will be helpful to physiologists, biologists, the medical profession and others primarily interested in health-maintenance as well as to physicists, engineers, and others interested primarily in lighting the indoor world.

The author gratefully acknowledges the aid of his colleagues, L. L. Holladay and A. H. Taylor in obtaining data; of B. L. Miller and T. K. Knowles in preparing illustrations; and of Miss Ruth Seaborn in proof-reading.

M. Luckiesh.

May 1930.

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CHAPTER I

A New Era of Lighting

Nature is beneficent—life-giving—but also ruthlessly destructive. Its eternal shower of blessings has not effaced or even dimmed the edict that only the fit shall survive. Knowledge, and the freedom and intelligence to apply it, are man's means of decreasing unfitness. They alone can provide some resistance—during the limited life-span—against the edict which inexorably takes its toll among the unfit and the unable living things. Having infinite time, Nature's efficiency springs from its inefficiency.

Primitive beings universally instinctively recognized the beneficence of sunlight, as is adequately shown by their customs, but to them Nature is also whimsical. Our early ancestors retired to caves and crude huts to escape dangers. Going indoors was, in a sense, a declaration of independence from Nature. Countless centuries elapsed during which the degree of independence slowly increased. Even some slight improvements over Nature developed. However, no great achievement in these directions was possible until human beings learned something of the laws and effects of the environment in which they and all living things evolved.

Here and there an individual, directing his eyes and his mind beyond the horizon of the obvious, began to inquire into the secrets of the natural world. Finally, a few centuries ago a great truth dawned—Nature could be understood and was worth understanding! Modern science was born and with it a more formidable declaration of independence from Nature was formulated. As a result much independence has been achieved and civilization has gone far beyond by improving upon natural environment in many ways.

Material civilization—our artificial world—has been pos-

sible largely through the production of artificial light. In this artificial world, which is the intent and the result of man's declaration of independence from natural environment, the opportunity of light-production has been to duplicate and to improve upon natural light and lighting. However, from the primitive pine-knot to the most powerful searchlight, the production of artificial light has been inspired by the single purpose of enabling the eyes to see. Every effort and consideration, excepting a few relatively recent ones, have been limited by this horizon.

During the course of lighting development quantity of light has received much more—overwhelmingly more—attention than quality or spectral character of light. Notwithstanding this, success has been greater in reproducing Nature's quality of light by artificial means than the quantity of light outdoors. In the indoor world we are still stumbling and abusing the eyes in relative darkness even though much greater quantities of artificial light are economically possible. Artificial daylight of proper spectral character has long ago been successfully achieved. Production of artificial light has far outstripped its utilization. Civilization, so dependent upon artificial light, is still almost entirely oblivious to the importance of lighting as a partner of vision in the act of seeing.

Controllability is the characteristic which has won most of the success enjoyed by modern artificial light. In this respect the natural environment has been greatly improved upon. Controllability of modern artificial light has led to many applications undreamed of in past ages. The electrical age gave to artificial light this prime characteristic which has enabled it to serve mankind admirably in the construction of his unique artificial world. Much of this success has been due to the simplicity, flexibility and divisibility of the electrically-heated filament bottled safely in a glass bulb. By dividing, enlarging or shaping the filament as desired, almost complete optical control of light has been achieved to meet a variety of needs and new possibilities with the result that electric lighting has far outstripped natural lighting in many respects. With every

decrease in the cost of light-production greater possibilities arise in controlling the quality or spectral character to suit the requirements. Likewise, with each decrease in cost it is possible to take another step toward those high intensities of illumination outdoors in the daytime which are the ideals toward which conservation and efficacy of vision are urging the intelligent user of the eyes. Already artificial light successfully competes with the cost of daylight indoors.

In the great drama of electric lighting which has been enacted for a half century the prominent rôles have been played by the arc and the filament-lamps. As practical devices they appeared upon the stage almost simultaneously. Then began a struggle for supremacy in many fields of artificial lighting as a necessary partner of vision. For years the battle raged. Temporary victory for one source was often turned into temporary defeat. The tide of fortune ebbed and flowed. After a quarter of a century the arc seemed to be doomed. It steadily lost territory. It clung doggedly to street lighting, to large interiors, and to certain special fields. Improvements in filament-lamps continued to press the arc on all fronts. It was forced from the streets but it still clung to photography and to certain small fields. At the present time the arc in lighting applications is chiefly represented by the carbon arcs in large searchlights and projection devices, by the mercury arcs in a part of the industrial field, and by special arcs in specialized applications.

The fifty-year struggle was won by the filament-lamp because behind it were greater safety, simplicity, flexibility, and divisibility. At the present time, as one views the thousand types of standard and special filament-lamps, ranging from a fraction of a watt to fifty thousand watts, the great advantages of these fundamental characteristics stand out clearly. Efficiency in light-production is important—but not all-important. Simplicity can overcome a large handicap in efficiency. And so it is with flexibility and the other factors. These lessons have been learned and they will influence future considerations.

Just as the filament-lamp surveyed its vast territories with

justifiable pride and the arcs were becoming reconciled to their meager fields, ultraviolet radiation stepped from a minor rôle in the drama to an important and popular one. For many centuries sunlight has been more or less vaguely recognized as being directly beneficial to human beings. Doubtless, even early primitive beings instinctively recognized its beneficence quite beyond its warmth and its essentiality to plant life—the foundation of all food for mankind. However, a systematic study of the curative and health-maintaining value of sunlight was not begun until the latter part of last century. Among the pioneers in this field Niels Finsen in Copenhagen and A. Rollier in the Swiss Alps are most prominent. About the beginning of the present century they had established sunlight and also ultraviolet radiation as curative and health-maintaining agencies. And then the first vitamin was discovered. Scientists trained their intellects and methods upon radiant energy as a vital factor in life and health. Some fundamental facts of great importance have been unearthed. Among these is the fact that certain radiations of wavelengths near the short-wave limit of the solar spectrum are very important in connection with a certain vitamin, in the cure or prevention of certain diseases, and in the preservation of health in general. What had been instinctively recognized or tacitly accepted for centuries began to acquire a scientific foundation one hundred years after the discovery (about 1800 A.D.) of invisible radiant energy of wavelengths adjacent to the visible spectrum. These are now known as ultraviolet and infrared.

Notwithstanding the great progress of scientific research in these directions, the subject as a whole is just emerging from the twilight zone of knowledge. It is in such twilight that irresponsible imaginations flourish. A great demand has been created for ultraviolet radiation in powerful quantities which would give an impressive erythema or sunburn. Apparently the theory was that the user must see an effect to be convinced that he was saved from some dread end or that he got his money's worth. The filaments of tungsten-filament lamps radiate desired ultraviolet radiation but in small quantities.

In the present stage of demand for high-intensity ultraviolet, these sources were ignored. The arcs came to life. Professional therapists had been using them for several years. Scores of outfits became available to the householder and wherever health is given some consideration the claims and uses quickly overflowed the boundaries of actual knowledge. There is no doubt that sunlight or its equivalent, and also ultraviolet radiation of wavelengths shorter than those in solar radiation, have curative and health-maintaining value but much research is necessary before many of the claims can properly be made.

For the moment let us ignore the unfounded claims and the myriad unanswered questions regarding the value of sunlight. For many years it has been obvious to those who direct their resources upon the future of artificial light and lighting that a new era of simulated sunlight was approaching. Before the recent furore of selling cure-all devices enough was known of the curative and health value of sunlight to indicate to the developers of artificial lighting that eventually lighting would have a dual purpose—for health as well as for seeing. Certainly it falls to the lot of those who have chosen to illuminate the artificial world—to provide this independence from the natural world—to create a quality of light which possesses as much of the value of sunlight as possible. As long as no direct benefits of sunlight upon human beings were known, excepting that it enabled them to see, the task of the producer of light was merely to satisfy the eyes. However, as other benefits were revealed by scientific investigation the developer of artificial lighting recognized a task of greater magnitude and importance. As a consequence he has been looking forward for years to a new era of lighting with artificial sunlight in its fullest sense.

This dream of simulating sunlight and dispensing whatever health benefits there are in midsummer sunlight while providing light for vision, has its beginning in the impressive logic of sunlight as a powerful environmental factor. It has been stimulated by many sound scientific facts and qualitative observations. As an environmental factor solar radiation takes

its place with air, earth and water. A survey of the natural world reveals these as the primordial elements required by living things. All life depends upon them. It is easy to convince a human being in one minute that he needs air. In a week he would admit that he needs water. Certainly the most determined hunger-striker has been convinced in a month that he needs food—the earth. It is easy to prove that human beings need solar radiation, indirectly at least. However, the urgency of a direct need for it has not been determined. It may be said that every human being needs solar radiation or a substitute for it in the form of certain foods. This is essential for continued health.

In discussing this new era of artificial lighting with the extended purpose of health-maintenance as well as for seeing, curative value may be eliminated. Illness and disease should be exclusively the territory of the medical profession. In curative value radiation from artificial sources has not only successfully challenged the sun but has achieved results far beyond those obtainable with sunlight. This is due to the fact that certain artificial sources supply radiant energy (gamma rays, Röntgen rays, and short-wave ultraviolet) not found in sunlight. In the new era of lighting, midday midsummer sunlight must be simulated sufficiently closely to be safe to use over long periods and with no more precautions than are necessary in exposure to natural sunlight. Health and the prevention of illness and disease are partially the territory of the medical profession but not exclusively. Each one of us as an individual and every science and art have territorial rights in the kingdom of health.

Medical men recommend sunlight and with the aid of allied sciences have proved that it is beneficial in some respects. Still we do not require prescriptions to expose ourselves to sunlight. Likewise persons who are not ill can as freely be exposed to artificial sunlight if its spectral character and the quantity of ultraviolet radiation are properly limited. Therefore, there can be no question regarding the right of lighting development to issue another challenge to the sun—

to extend its purpose to the production and distribution of simulated sunlight, adequate and proper for seeing, and in addition to supply health-benefits of sunlight to those who work and play in the indoor world. From such an artificial sunlight supplying proper intensities of health-maintaining radiant energy no less benefit is to be expected than from midsummer sunlight—and much more benefit is possible than from summer sunlight in smoky cities and from winter sunlight everywhere in middle and higher latitudes. Summer sunlight is valuable to those who have the opportunity to expose themselves to it adequately. It loses its value when transmitted through ordinary glass; it is usually inadequate indoors and also often outdoors; and it is undependable. Opportunity has arrived for safe, simple, and adequate artificial sunlight.

As civilization advanced mankind became more and more engrossed in the construction of the artificial world and more and more an indoor being. In fact, civilization may be measured largely by the indoorsness of living and working. In early centuries daylight had to be depended upon in buildings because the smoky flames of crude materials accomplished little toward adequate light. Openings for admitting daylight naturally became the standard practice. When the age of electric lighting dawned, daylighting of interiors had become entrenched by long practice. Even at the present time when adequate controllable artificial light is economically possible, architecture and the indoor world are suffering from the daylighting habit. Blindly, without proper consideration of cost and inadequacy of daylight indoors, natural lighting is practiced by time-honored means.

Particularly in congested cities, valuable ground and floor areas are being wasted to admit inadequate and uncertain daylight indoors. Wall space is being consumed by windows. Architecture is being handicapped by the window and skylight habit. Set-backs of upper stories are demanded by ordinances. These losses combined with heat losses, investment and maintenance charges are mute evidences that the development of artificial light and lighting has overtaken and passed most

persons because of retarding habits acquired before the age of modern controllable and relatively inexpensive artificial light. Daylight equipment to let light in and to "let vision out" should be installed where it can be useful at a reasonable cost. But artificial lighting is always necessary as insurance against the failure of daylight. Glimmerings of the change in relationship between natural and artificial light are permeating the blinding fog of habit. Certainly the new era of artificial lighting with simulated sunlight will lend emphasis. Ordinary glass does not transmit the health-maintaining radiant energy and the almost total absence of these for many months in smoky cities and in middle latitudes emphasizes the undependability of daylight. Certainly, in many respects modern artificial light and certain promising artificial sunlights have not only successfully challenged the sun but have far surpassed daylight as an illuminant for seeing and for health-maintenance in the present intricate artificial world.

In order to enter this broader phase of artificial lighting new data obtained from this new viewpoint are needed. The established principles of adequate and proper lighting are available for a foundation. To this the new data must be applied in order to remodel the lighting structure. Considerations of lighting in the old and narrower sense need not be discussed in this treatise excepting as they cannot be separated from the new.

Naturally, the available sources are of interest. They are the carbon arcs, the mercury arc, tungsten-filament lamps, tungsten arcs and a very interesting new source—a tungsten-mercury arc known as the Sunlight (Type S-1) lamp. This new source consists of a tungsten filament in parallel with a mercury arc between tungsten electrodes. No moving parts are necessary to operate it and in simplicity it ranks with the filament-lamp. Tungsten-filament lamps are promising. During the stage of demand for powerful sources of ultraviolet radiation only the arcs and the new Sunlight (Type S-1) lamp appear suitable to the superficial observer. Those whose experience has been gained only in therapy or with home-

treatment equipment are likely to consider that artificial sunlight in order to be valuable must produce a perceptible erythema with a relatively short exposure—a matter of minutes. In lighting for health and vision the health-value will be obtained as automatically as it is outdoors—while persons are engaged in some activity. The amount of ultraviolet radiation must be such that persons may work or read or engage in any activity for hours without over-exposure. This demands a lesser quantity of ultraviolet radiation than for the quick treatment. In fact, the dosage must be determined in terms of footcandles. Fortunately, there are wide limits which make it possible to produce artificial sunlight as safe and practicable as outdoor natural sunlight.

With home-treatment sources of ultraviolet radiation a visible erythema, appearing a few hours after exposure, is usually insisted upon. Physicians use this as a gauge of dosage and laymen consider it evidence that they have received some benefit from the treatment. Erythema has been so closely associated with sunlight substitutes that it is generally considered to be necessary in order to receive benefit. It has been proved that this is not true. Even tanning is not necessary nor does it prevent the radiant energy from being beneficial. Erythema is evidence that a certain dosage—the product of intensity and duration of exposure—has been received by the skin. Tanning is evidence of exposure to ultraviolet radiation. A good tan does not close the doorway of the skin to the benefits of further exposures but it affords protection from over-exposure within certain reasonable limits.

An artificial sunlight for general use in lighting for health as well as for seeing must not be harmful to the eyes unprotected by glasses. It is well known that the short-wave limit of the solar spectrum is at λ2900.* In winter and at other times when the sun is at low altitudes the limit is at a somewhat longer wavelength. Often under these conditions the solar

* In this book all wavelengths unless otherwise specified are expressed in Angström units. The Greek letter lambda, λ, signifies wavelength and the expression λ2900, for example, means, "a wavelength of 2900 Angström units."

spectrum does not extend as far as λ3000. The ultraviolet radiation known to be physiologically beneficial is chiefly that between λ2800 and λ3100. Doubtless ultraviolet radiation of the longer wavelengths will be found to play some part in life-processes when the entire subject is sufficiently explored. However, for the present, interest is centered chiefly upon the region indicated above.

In producing artificial sunlight for general lighting a very important consideration is the intensity of illumination outdoors. During midday on a clear day in summer the intensity of illumination from the sun and the sky sometimes reaches 9500 footcandles. It is commonly above 7000 footcandles. If an artificial sunlight is to be as effective (as measured by the production of erythema) as midsummer sunlight, it must have much more of the erythemal rays per footcandle than outdoor midsummer sunlight. Indoors 100 footcandles is erroneously considered a very high level of illumination by means of artificial light. If 100 footcandles of artificial sunlight is to be as effective in this respect as 8000 footcandles of natural sunlight, the former must have 80 times the erythemal effectiveness per footcandle as the latter. If the duration of exposure to this artificial sunlight can be eight times as long the erythemal effectiveness need be only ten times as great per footcandle. If the footcandles of artificial sunlight are decreased then the ultraviolet content must be increased. We have studied these relationships so that such considerations can be taken into account as shown later.

Obviously owing to the much higher levels of illumination under natural sunlight than those in use in artificial lighting an artificial sunlight must have a much greater erythemal effectiveness than natural sunlight. This can be accomplished in two ways: (1) by extending the ultraviolet spectrum as far as possible toward shorter wavelengths without harm to the eyes and (2) by providing a higher percentage of energy of the short wavelengths, as compared with the total energy, than is found in sunlight. Both these expedients have been investigated. We have found that λ2800 is a safe short-wave

cutoff under reasonable exposure to proper intensities of artificial sunlight. Many exposures of the eyes of subjects have been made with considerable energy of this wavelength and even some energy of shorter wavelengths without any indication of conjunctivitis (inflammation of the outer membrane of the eye). Other data obtained years ago support this conclusion. Of course, conjunctivitis (snow-blindness) is produced by long exposures to great amounts of sunlight reflected from snow. The harm depends upon quantity as well as wavelength within certain limits. These are examples of the new data and viewpoints which must be added to the foundation already established for lighting.

In lighting for health as well as vision the ultraviolet must be conserved as well as light. Many blunders have already been made by assuming that materials which efficiently reflect visible radiation—light—also efficiently reflect ultraviolet radiation. As a matter of fact few substances do this. Generally, materials are inefficient reflectors of ultraviolet radiation. Sufficient data are now available to proceed without difficulty with the development of lighting with sunlight substitutes. Surfaces of walls and ceiling may generally be assumed to be unsuitable for reflecting ultraviolet. Doubtless with the growth of this new lighting these will be altered for the purpose but, for the present, fixtures directing the light downward rather than upward to the ceiling will be more practicable. In order to maintain the effects found desirable in good lighting practice, auxiliary lighting by means of tungsten-filament lamps may be utilized. In fact, this is a very practicable expedient for controlling the quantity of ultraviolet radiation per footcandle.

Proper lighting requires not only efficient reflecting media of various characteristics but also diffusing transmitting media such as translucent glass. A diffusing quartz is now being fabricated into various forms and its cost is not prohibitive. In fact, with the development of adequate volume such materials can be manufactured at a satisfactory cost. Quartz efficiently transmits ultraviolet radiation as far as λ2000. A safe artificial

sunlight should have a short-wave limit at about λ2800 so the spectral transmission of quartz extends further into the short-wave region than necessary. This is not a handicap provided the quartz envelope is not depended upon to limit the short-wave cutoff of the spectrum of the artificial sunlight. In practice it is much safer to have the container of the light-source perform this function rather than the diffusing shade or envelope. Glasses can be made which efficiently diffuse the light while transmitting the desired ultraviolet radiation. Therefore, with diffusing quartz and special glass combined with certain efficient reflecting media the necessary materials are available for adequately controlling artificial sunlight by means of lighting equipment.

Having briefly discussed the need for artificial sunlight, its production and control, the major details of the picture become complete by a glimpse of the fields of application. It was very natural that artificial sunlight was first applied by the medical profession for its curative value. With studies of its preventative value it naturally found its way into the home and other places where health-maintenance is of primary interest. Portable equipments supply these demands very satisfactorily. Unconsciously anyone who has performed a visual task, such as reading while exposing himself to a safe artificial sunlight without wearing goggles, has inaugurated for himself the new era of lighting in its simplest form.

With the initial awakening to the fact that civilization had quite generally forsaken the sun, interest in more general applications awakened. With these possibilities in mind producers of light augmented their efforts to supply safe, simple substitutes for sunlight which could supply light for seeing and radiation for health-maintenance. With these available, the next steps in a logical development of artificial sunlighting are into those places where health is of primary interest and lighting for seeing is secondary. Nurseries, gymnasiums, swimming-pools, play-rooms, solariums, are examples. Then come school-rooms, and finally the work-world of our indoor civilization and even places where we read or rest at the end

of the day. For most of these fields the ceiling-fixture is the most suitable.

All these developments are under way but, as we have learned from lighting in the older sense, the work is never done. New applications inspire new developments and so on, decade after decade. Even in ordinary lighting after a score of years of intense development and application the era of adequate controllable artificial light has barely begun. Many goals are still visible far off and many are over the horizon, seen only in the imaginations of a few persons. Still others are undreamed of. Upon such a scene of proud accomplishment and great opportunities for artificial light to aid and to appeal to the eyes, this new era of artificial sunlight arrives. It is reassuring, if such is necessary, to both the producers and users of artificial light that this part of the construction of the artificial world—material civilization—is going forward. Artificial light has made man's unique indoor world possible. In a sense it is at the head of the procession—the torch—of civilization. Man, the only animal that is continually evolving in independence, the only one who is inoculated with appreciation and defiance of Nature, the only one who worships and challenges the Sun, succumbs to Nature eventually. But before doing so the modern doers smilingly (being also the only animal that laughs) unravel the secrets of their natural environment and apply them in myriad combinations in the artificial world—making themselves and the human family happier and more fit. Their declaration of independence rings out more confidently with each passing decade.

CHAPTER II

The Sun's Beneficence

Countless details may be mustered to prove that the sun is overwhelmingly important to life upon earth but much of its influence upon the life and health of human beings is indirect. To separate from this multitude of scientific facts the direct beneficence of sunlight is relatively a much more difficult task. However, the general use of artificial sunlight in dual-purpose lighting—for health as well as for seeing—must be based upon direct benefits. The difficulty arises from the extreme complexity of the human organism and the incompleteness of scientific knowledge owing to the newness of biological and physiological sciences.

The visible spectrum was discovered in 1666. This was the first experimental evidence that the radiant energy from the sun possesses various wavelengths or frequencies. Half the time had elapsed since that achievement of Newton before the ultraviolet and infrared spectra were discovered. Physical science was in the making and it had to become reasonably well founded before chemistry could develop. Chemical science had to become well founded before physiology could go ahead with certainty. And so on to biology, psychology, sociology and the allied sciences involving human beings. One science is founded more or less upon at least another science and the development of the chain is necessarily slow. Furthermore, as the science deals more with living matter and finally with complex organisms, it becomes less and less exact and must depend more and more upon statistical data. For example, a physiological effect upon one individual is interesting but usually means little more. The same cause must produce the same effect upon many persons under approximately the same conditions to become a scientific fact. Therefore, cura-

tive, preventative and health values of sunlight are difficult to establish and the difficulty increases rapidly in the order given.

A great deal of conscientious effort has been expended by biologists, physiologists, and physicians in investigating the influence of radiant energy upon diseases. However, much of the value of these researches is lost because of inadequate control or specification of intensity and wavelengths of energy employed. Furthermore, most of the researches not open to this criticism are not directly helpful for the present purpose because, when artificial sources of radiation were used, energy of wavelengths far outside the solar spectrum was present. Finally, most of these investigations have involved only the cure of disease. Regardless of the many outstanding successes achieved in the cure of diseases by means of solar radiation or approximate artificial sunlight, these are only of secondary value in establishing health-maintenance. They are valuable supports for the superstructure which none doubts is an elaborate one but which at present is visible only as a more or less disconnected framework.

Instinctive recognition or use of sunlight as a remedy, a preventive, an adjuvant, or a tonic cannot be considered to be scientific proof of its powers. However, such instinctive procedure persisted in by human beings for centuries acquires considerable weight. Its naturalness eventually gives it some authority which must be reckoned with, the more so after it becomes supported by even a few isolated facts. Until the beginning of the present century this was approximately the status of the attitude toward sunlight in regard to its direct effects upon the life and the health of human beings.

Sunlight is a very old remedy. The same instinct which led primitive beings and even early civilized peoples to worship the sun as a deity led them also to believe that its radiation possesses therapeutic value. Since the earliest historical time there is plenty of evidence that it was used in the treatment and prevention of disease. The Egyptians treated the sick with it. Hippocrates, who may be considered the father of

medicine, had something to do with the erection of a health temple dedicated to the tri-deity—sun, music, and medicine. The Romans built solariums with unglazed openings. Herodotus is quoted as stating that sunlight "is especially necessary for people who need restoration and the increase of their muscles." . . . It is surprising that his statement also revealed even a vague idea of what was not scientifically settled until relatively recently. The exactness of early knowledge in some directions is illustrated by another part of the quotation—"One must further take the precaution that in winter, spring and autumn the sun strike the patients direct; in summer this method must be avoided by weak people." . . . Arabians and other peoples many centuries ago practiced sunlight treatment. Eventually among the peoples which flowed northward and westward in Europe the use of sunlight in this manner seems to have waned. Apparently its use even became stigmatized as quackery. From observation of the past decade it is not difficult to imagine how this reversion came about. Quackery flourishes in the twilight zone of knowledge. Likewise, something closely akin to it develops during the same period—practices based upon unquestionable sincerity but lacking adequate knowledge of the nature or of the effects of the alleged remedy. The entire gamut of attitudes, claims and practices has existed during recent years but, fortunately, favorable results of scientific researches have been saving the situation. In earlier centuries the latter were lacking and heliotherapy had scarcely emerged from the darkness. Therefore, it is not surprising that sunlight therapy to some extent fell into disrepute from which it emerged with difficulty.

Near the close of the eighteenth century Faure definitely advocated the treatment of chronic ulcers of the skin by means of sunlight. Later, more scientific work seems to verify his claim. Others began to interest themselves seriously. For example, Chauvin published a treatise entitled "Insolation" in 1815 in which he advocated the use of sunlight in all diseases with which feebleness, exhaustion and apathy were associated. The invisible radiation of shorter wavelength than the short-

wave limit (violet) of the visible spectrum had been discovered about fifteen years before. However, nearly a century was to elapse before much of the direct benefit of solar radiation was scientifically established as due to ultraviolet radiation near the short-wave limit of the solar spectrum.

Toward the close of last century the names of Niels Finsen and A. Rollier became conspicuous in actinotherapy and heliotherapy. To them is due much of the credit for a triumphant advent of sunlight and radiant energy from artificial sources into modern scientific medicine. They are responsible to a large degree for what was a re-entry of these agencies into the good graces of the medical profession and the public. These have come to stay for they have stood the test of quackery, extravagant claims, misuses and scientific investigation.

Finsen demonstrated decisively that tuberculosis of the skin (lupus vulgaris) is cured by the direct application of ultraviolet radiation. He contributed much in the development of methods and technique. The Danish government honored his achievements by establishing the Finsen Medical Light Institute after his death in 1904.

In the same year that this modern pioneer died, Rollier created an institution in the Swiss Alps for sunlight treatment and a scientific study of the results. He achieved notable results upon anemia, rickets, chronic ulcers, and tuberculosis of the skin, bones, glands, and joints. He not only investigated the curative value of sunlight but formidably studied the more important matter—prevention of disorders. His work, carried on extensively after Finsen's elaborate re-introduction of sunlight into medical practice, was largely a source of inspiration for many scientific investigations during the present century, just as Finsen's work certainly inspired much of his efforts. Largely to these two men sunlight owes its Doctor's degree. Dr. Drugs no longer monopolizes as much of medical practice as formerly. Dr. Sunlight or his indoor understudy is achieving wonders as is Dr. Diet.

Statistics already yield much evidence that sunlight is of direct benefit to human beings and in the light of present

knowledge adequately maintained records in hospitals, government bureaus, etc., will eventually clarify many of the present foggy places. In Fig. 1 is shown the relationship between the death-rate and the average number of hours of sunshine for each month of the year. The death-rate is the average for two years in the United States. This chart is typical of many which can be produced with statistics in this country and in European countries. During the winter months the sun is at lower altitudes and the maximum possible duration

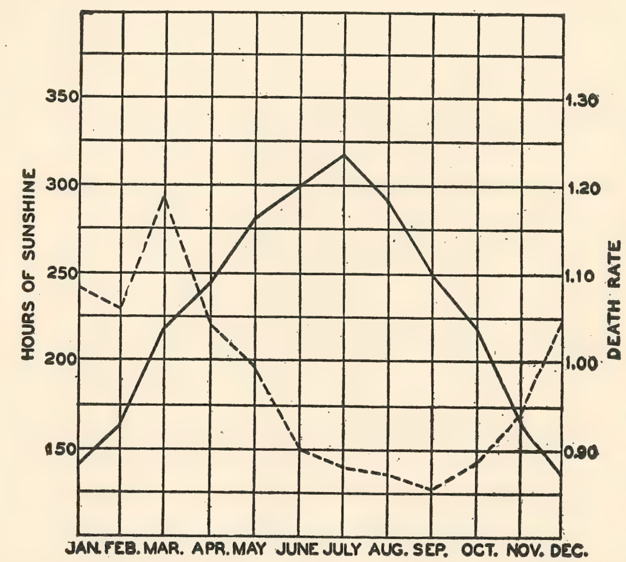

Fig. 1. Typical relationship of relative death-rate and average hours of sunshine for each month in the year (average for two years) in the United States.

of sunshine is much less than in summer. Furthermore, the solar radiation must pass through a greater air-mass as it reaches the earth more slantingly. As a consequence, the vital ultraviolet radiation in sunlight is greatly weakened in the winter months. This reduction in the quantity and the accompanying alteration in quality of winter sunlight is responsible for the increase of certain diseases and certainly is partly responsible for the higher death-rate during the winter months than during those of more and better sunlight. Such evidence

alone is not conclusive because many other factors are different in winter than in summer. However, considered with certain established facts it is impressive.

During the winter months human beings are confined indoors almost entirely. As a consequence they receive practically no sunshine, such as it is in biological effectiveness. Of course, living indoors in winter involves a different condition of humidity, ventilation and other factors. However, it is believed by many authorities that the lack of vitalizing sunlight is partly responsible for physical weakening which makes the inroad of illness and disease much easier. Common colds, pneumonia and influenza are more prevalent in the seasons and regions of reduced quantity and deteriorated quality of sunlight.

Most persons living in climates which curtail the amount of outdoor life during winter, experience a gradual decrease in vitality so that toward the end of the winter months their resistance, energy and enthusiasm are low. Even the cloudiness and decreased hours of sunshine cause mental depression which is not conducive to getting well or to remaining healthy. Morbidity increases as winter progresses and adequate light is so natural that it is psychologically important. For example, we have found that the performance of a purely tactual task was somewhat more rapid when light entered the eyes (through frosted goggles) than when no light entered them. The stimulative effect of light was demonstrated by the more work accomplished under the former condition in a given time.

In England mental tests given to children attending sun classes revealed an improvement in mental capacity and general alertness. Tubercular children who took sunbaths averaged in mentality a year ahead of children not so exposed. Those in charge claim that children entering the sun class were listless and lazy but as time passed they showed marked improvement in initiative and self-reliance. Some of this may be due to increased health but it is difficult to resist the mood of a sunny day. The brilliant sun overwhelms depression excepting in the cases of greatest depth. Sunless days are the suicide days.

Adequate lighting with artificial sunlight is of health value through the channel of the mind as well as through the skin and various physiological processes.

Much evidence indicates that artificial sunlight reduces the incidence of common colds. Maughan and Smiley [1] have shown that ultraviolet radiation decreased the number of colds in a group susceptible to them by forty per cent compared with a similar group not irradiated. They point out that the lack of ultraviolet radiation is only one of several known factors involved in reducing bodily resistance to acute respiratory infection. The control of this factor alone must not be expected to be a complete panacea for the prevention of colds. However, their results justify the claim that artificial sunlight is effective and important. Irradiation with a high intensity of radiant energy to the extent of producing perspiration may possibly result in catching cold through careless exposure immediately afterward. This is an example of the difference between high-intensity infrequent exposures of short duration and long exposures to moderate intensities as would be the case in general lighting for health and vision combined.

There is evidence that sunlight or approximately the equivalent radiant energy increases the resistance to infection. It seems to play an important part in the development of immunity to infection. How this is achieved is not known, but it is likely to be as complex as any general tonic such as fresh air and exercise. Ultraviolet radiation of nearly all wavelengths possesses more or less powerful bactericidal power. It will kill germs directly but if there is any destruction of microbes in the body it must be accomplished indirectly. Such radiant energy penetrates bodily tissue very slightly. In a general use of artificial sunlight germs in the air or on the surface of the exposed portions of the body would be killed and the general surroundings would be constantly sterilized. This should be a valuable by-product of the new era of lighting, resulting in health-maintenance by diminishing the spread of microbic diseases. The sun is continually sterilizing the earth, rendering water fit to drink and in general holding

within bounds the myriad germs which otherwise would soon rule the earth.

Sunlight has been proved effective in the treatment of many diseases which, as already stated, add something of value in considering health-maintenance. Rickets, anemia, infantile tetany, many forms of tuberculosis and various skin infections have yielded to it. Besides these and other diseases it has proved valuable as a tonic in convalescence, anemia, muscular weakness, general debility and acute infection. Apparently, anemia is due to the inability of a person to utilize iron in a manner to develop a normal amount of hemoglobin—the coloring matter of red corpuscles containing iron. The prevalence and severity of anemia are greater in winter than in summer. There seems to be no doubt of the effectiveness of sunlight in promoting the assimilation of iron and in producing hemoglobin and red corpuscles in the blood. Secondary anemia is quite common and many persons earn their living in the work-world in this condition. Certainly artificial sunlight as an environmental factor in the indoor world would be helpful to them.

It is claimed that sunlight, its ultraviolet equivalent, and vitamin D possess the ability to increase the acidity of the stomach. The acid destroys bacteria which come from the mouth and the large intestine. The acid from the stomach flows into the small intestine where it is helpful. Without this acidity bacteria are likely to prosper and eventually penetrate the walls, enter the blood stream and begin an infection at some point of weak defense. Besides this, if the small intestine is alkaline or neutral the iron is not absorbed but passes out of the body unused and anemia results. Likewise, calcium and phosphorus are lost by not being assimilated. The result is rickets or soft uncalcified bones, particularly in children.

Perhaps the most outstanding, complete, and successful study of the importance of sunlight or its artificial equivalent is that in relation to the prevention and cure of rickets. Attention was attracted to sunlight in relation to this disorder by the striking seasonal incidence. Rickets occurs with marked

frequency during the winter and early spring and almost disappears in midsummer. This nutritional disorder is comparatively rare in the tropics or in sunny countries where much outdoor living is the rule. It is particularly manifested in the softness and lack of growth of the bones of children but a similar disorder has also been reported among the women of certain countries where custom secludes them indoors. Sunlight, or its equivalent, influences the storage of calcium and phosphorus in the bones and affects the equilibrium of these elements in the blood stream in adults as well as in children. Ultraviolet radiation of certain wavelengths, or Vitamin D in food, promotes calcium anabolism, curing and preventing rickets, promoting growth, and preventing excessive loss of lime from the body.

Radiant energy of proper wavelengths or Vitamin D, revives or aids a depressed function; neither creates new processes. The technique in the study of radiant energy in curing rickets has been highly developed. For example, the effect of one exposure to artificial sunlight can be detected by blood analysis for a month or two, and sometimes for three months, when the dosage has been sufficient to cause an erythema. However, reddening of the skin does not seem to be necessary to cure or to prevent rickets. A definite improvement in rickets has been achieved with long exposures to low intensities of the mild ultraviolet radiation from tungsten-filament lamps in special bulbs. Certainly erythema cannot be produced upon the average skin under the conditions which produced this improvement. Most of the work on rickets and other disorders has been done with large dosage productive of erythema. For several years we have had the co-operation of various physiologists who have found that comparatively mild ultraviolet radiation produces favorable effects. The threshold value of dosage has not been determined but it is well below the intensities of illumination and radiation which are quite practicable in lighting for health as well as for vision.

The prevention of rickets by means of artificial sunlight is well established. Therefore, regardless of any other direct benefits the use of a satisfactory artificial sunlight is practicable and desirable for the indoor world which children frequent. Nurseries, play-rooms, and even school-rooms should be among the first to become enrolled in this new-era lighting of extended purpose.

One of the vitamins, fat-soluble D, possesses a biological effectiveness similar to ultraviolet radiation of certain wavelengths present in sunlight and in radiation from certain artificial sources. It is present in such fats as are found in cod liver and the yolks of eggs. Such foods prevent rickets just as sunlight does but whether or not the effects of food and of sunlight are wholly identical is not entirely proved. This vitamin is created by sunlight. Many foods contain ergosterol or a very similar compound. Ultraviolet radiation of certain wavelengths showered upon such foods creates vitamin D or is stored for future use. This is proved by irradiating such a food which does not prevent rickets and converting it into an effective preventive of this disorder. Thus, ultraviolet radiation adds very important nutritional value to foods. The vitamin D in cod-liver oil which served mankind before its existence was discovered is doubtless traceable to the effect of sunlight. Scientific research has just begun in earnest to unravel a tangled skein. This discovery of the production of vitamin D in cod-liver oil and perhaps in the ergosterol of the human skin is extremely fascinating. It opens a vista to the imagination which includes the life-processes of all living things. With such facts before one it is difficult to conceive that sunlight, having bathed the earth for ages, has not interwoven itself into life-processes so inextricably that science will be long in ascertaining all the details of the truth and in getting along without it or its artificial substitute.

In such a vista, chlorophyll impresses one with an overwhelming importance. This green coloring matter in the leaves of plants is a powerful connecting link between sunlight and all life on earth. It utilizes solar radiation of certain wavelengths in fixing the carbon from carbon-dioxide gas into the plant structure and performs other important functions. All

life eventually lives upon plants. Human beings breathe oxygen and require certain minerals and elements in plants whether eaten directly or indirectly by eating animals which eat them. Thus we live largely upon carbon supplied by the plant kingdom just as the machines we build receive their energy from the coal which chlorophyll made eons ago by fixing the carbon in the luxurious vegetation of that far-off carboniferous age. Such a view sees sunlight as the life-blood of Nature—the giver, the preserver, and the prolonger of life.

Chlorophyll, which manufactures carbohydrates by utilizing sunlight and storing its energy in starches and sugars, has a close relative in hematin or hemoglobin, the red coloring matter in the blood. It is quite likely that it is very closely related to the blood. Some authorities go so far as to propose that the hemoglobin is probably formed in the body from the chlorophyll. The chemical constitution of the two is similar excepting that the green coloring matter of plants contains magnesium and the red coloring matter of blood contains iron. There is something more than fancy in the analogy of human beings to leaves of trees. Both eventually wither after serving their purpose. In the fall of the year or of life they have completed their work. Certainly, both depend upon sunlight—plants directly and human beings partially so at least. Animals having the ability to move about may have evolved a degree of independence of sunlight through indirect use of it and through some ability to store its effects so that they can live without its direct beneficence for relatively long periods. At any rate there is more than a mere analogy between human beings and leaves of plants.

In any locality there is a wide range of solar radiation. Northern exposures, the sunny southern ones, the eternal shade of the glen or suppressed sunlight of the deep woods all have plant life adapted to those environments. Likewise over the earth from the tropics to the polar ice-caps and from sea-level to timber line is a great variety of environments. Some are places of eternal sunshine and others of brief summers and long dark winters. All these have plant life adapted to live

full, fruitful lives. And all these plants, through the use of whatever solar radiation is available, convert lifeless matter into living matter. Plants do not live normally in the darkness excepting possibly a few crude forms.

Likewise human beings are found over the earth in a variety of climates and under a variety of quantity of solar radiation. But their ability to move about takes the white people of temperate zones to live in the tropics and deteriorate from too much heat and sunlight. It takes men to the polar regions where they survive owing to intelligence, vitamin foods, and perhaps a biological ability to store for long periods the beneficence of sunlight. Nature has provided pigmentation as one means of adaptation. One may develop a tan to aid him in adapting himself to sunlight. If the change is not too great he can live healthily. However, the white man cannot become perfectly adapted to the tropics in a season or even in a lifetime. The negroes and others high in the scale of brunetness are adapted in the matter of pigmentation as well as in other ways. To them the tropics have become a natural habitat through centuries of adaptation.

When more is known in regard to solar radiation it is likely that the migrating of Northern blondes to the tropics and bringing the negro to middle and Northern latitudes will both appear to be acts of blind ignorance. When people naturally migrate and live vigorous happy lives generation after generation, it is evidence that the change has not been more than their adaptive ability could span. For example, the virile blondes of Scandinavia seem to migrate to Minnesota and the Northwest where the degree of sunshine is reasonably comparable with their native land. The American Indian was perhaps properly pigmented for a complete outdoor life in this country. In degree of brunetness he is midway between the black and the white races. On the same basis should the Esquimo be white? Not necessarily, for he lives an outdoor life bitten by wind and exposed to much sunlight during an intense although brief summer. The degree of outdoorness of living is a great factor even among the white race. Com-

pare the swarthy daily golfer or the Mediterranean fisherman with the indoor workers.

There is a variation in the ability of persons to tan. Certainly, there is another factor in pigmentation besides merely the degree of exposure to sunlight. Perhaps this accounts for some of the seeming inconsistency; for example, the Esquimo. Tanning is taken too seriously as an indication of health. Some persons do not tan. These are low-scale brunets. The albino would be zero on the scale of brunetness. It is stressing knowledge too far to say that so-called blondes who burn rather than tan are not healthy for in general they may be. However, there is some evidence that those who tan well respond better to heliotherapy than those who do not. Furthermore, it seems that those who tan well have a fundamental ruggedness not quite equalled by those who do not. Possibly tanning is not wholly a defensive reaction which is a protection from reasonably large over-doses of sunlight. It may be partially an adaptive response which makes the person who tans well more able to utilize the benefits of sunlight or similar radiant energy.

In the natural environment early primitive beings were generally less clothed than civilized peoples of the present time. Doubtless clothing was gradually adopted as the primitives migrated or as the climate changed. At any rate, this adoption must have been gradual; complete nakedness eventually gave way to partial exposure of the skin. The entire effect this has had upon health is unknown but it is obvious that human beings and their organic processes are endowed with very large factors of safety. Without such endowment the human race perhaps would never have existed and certainly would not have survived the different environment produced by migration and by civilization's indoor world.

Naturally the question arises as to the amount of skin which must be exposed in order to obtain direct benefit from sunlight. Much remains to be learned in regard to threshold dosage and skin-area permissible. However, we are already certain that the threshold dosage is far below that of outdoor

sunlight and, of course, in the indoor world the duration of exposure may be controlled to suit the requirements. The intensity of effective ultraviolet radiation per footcandle may be altered to suit the hours spent under artificial sunlight and the area of skin exposed. There is always the possibility of combining in lighting equipment the light-sources merely for vision with dual-purpose sources of light for vision and radiation for health-maintenance.

The large factor of safety with which the skin is endowed and the adaptability through tanning greatly extend the range of intensity of radiant energy to which human beings may be safely exposed. Certainly the direct application of ultraviolet radiation to the skin creates a product or stimulates a process which pervades the body. To accomplish this the doorway need not be the entire surface of the body. As the area is restricted the exposure must be increased. The actual threshold relationships of skin-area, exposure-time, and intensity of radiation are not exactly known. However, there are adequate data and experience to assure us that the skin not covered by indoor clothing provides a doorway sufficient for the body of healthy or moderately healthy persons to enjoy the beneficence of a properly controlled artificial sunlight. In the matter of clothing women have outstripped men. Besides their hands and face they expose considerable areas of the neck and arms. Short dresses and sheer hosiery expose much of the area of the legs. Combined with this there must be the advantage in ventilating the skin because this is a natural environmental condition.

In much of the work-world men work with shirt open at the neck and with arms exposed. Possibly the new-era lighting may influence men's clothing in the indoor world. If it does, another indirect benefit of artificial sunlight will be enjoyed by men who have remained bundled in uncomfortable clothing while women have made sensible progress toward ease. If men in the more conventional part of the indoor world continue to expose only hands and face, artificial sunlighting can be designed to fit the condition. However, the much abused

bald-headed men will enjoy the advantages of a greater factor of safety in exposed area of skin. Furthermore, some success has been achieved in treating baldness. Possibly bald-heads may disappear. At least they have nothing to lose and everything to gain.

With the development of heliotherapy and actinotherapy the skin assumes a new rôle of considerable importance. With increasing knowledge it appears more and more to be a complex organ. No longer is it to be considered merely a protective covering or a boundary between the human organism and its environment. The skin performs important and complex functions. It contains receptors for heat, cold, touch and pain which send warnings to the brain. It may contain receiving-stations for radiant energy which supply something which governs cellular activity. At least ultraviolet radiation of certain wavelengths incident upon the skin does something such as producing the mysterious vitamin D which eventually makes calcium and phosphorus deposit in the remote places in the body and achieves other wonderful results at a distance. Dermatology is concerned with local effects.

Perhaps human beings are closely akin to leaves of plants. A blade of grass is nearer to a human being in organic complexity than most persons realize and possibly is as important in the general scheme of Nature as human beings are. Man, in his egotism and in the rôle of umpire and using his own rules of comparison, will not generally admit this possibility. However, if he is to use sunlight or its equivalent in the indoor world he must turn to the blade of grass for information. When he has fathomed its life-processes he too will have a place in the sun although in his indoor world it will be a sun of his own making. The blade of grass devoid of a means of locomotion is protected from making mistakes. It remains in the environment where it was born and to which it is adapted. Who can say how much human beings have blundered by leaving their environment? At least man can now recreate that important part of his environment which he left behind when coming indoors. The sun's beneficence which he left

outdoors is now available in adequate biological effectiveness and controllable in quantity and duration. Again, material civilization has not only simulated a part of Nature but has improved upon it to meet the variety of needs which indoor independence demands.

CHAPTER III

Solar Radiation

The sun is analogous to a radio sending-station. It is continually emitting electromagnetic energy of a great range in wavelengths. Some of these are filtered out or otherwise lost in the atmosphere. Finally, solar radiation as we know it reaches the earth's surface where human beings and myriad forms of life are living at the bottom of the aerial ocean. Here at the earth's surface many receiving-sets (for example, photochemical processes) are tuned in for their specific range of wavelengths. Human eyes evolved so that they utilize energy of certain wavelengths to appraise the world at a distance—a marvelous sense indeed. Chlorophyll, another receiving-set, utilizes solar radiation of certain wavelengths (largely in the visible spectrum) and stores solar energy into starches and sugars. Ergosterol, a highly selective set, stores a marvelously vitalizing something—vitamin D—under the action of a narrow range in wavelengths. And so it goes with thousands of photochemical reactions and other receiving-sets, each of its own selectivity. Wavelengths and frequencies—truly this is a vibrant world of living things!

All the energy of various wavelengths which reaches the earth and is not reflected is converted into energy of another form. Most of this is converted into heat and a small part is converted into chemical energy of growing plants. According to Abbot, the maximum intensity of solar radiation (actually radiant power) near sea-level at Washington, D. C., varies from 1.15 to 1.45 calories per square centimeter per minute on cloudless days. At Mount Wilson, over one mile above sea-level it ranges from 1.45 to 1.62 and at Mount Whitney nearly three miles above sea-level, it is about 1.75 calories per sq. cm. per minute. This energy is sufficient to melt a layer

of ice 400 feet thick per year. However, plants utilize only about one per cent of the solar energy incident upon their leaves. An acre of ground will receive from spring till fall solar energy equivalent to several hundred tons of coal but the heat-value of the crop will be equivalent only to a fraction of a ton of coal. Nature is very inefficient in these processes but, then, with such a myriad of processes and functions to reconcile, great factors of safety are necessary. Nevertheless, man need not be ashamed to face Nature with the degree of efficiency he has been able to achieve in many energy-transforming processes which he has devised.

At the bottom of the ocean of atmosphere human beings are in an environment greatly influenced by this great filter of atmosphere and the water-vapor and impurities which it contains. The short-wave ultraviolet emitted by the sun disappears—perhaps due to absorption by ozone—before it reaches the earth's surface. This is chiefly responsible for the short-wave limit of the solar radiation as it reaches us. The impurities, such as smoke, secondarily influence the wavelength limit. The atmosphere and its impurities also selectively scatter the radiation from the sun. The visible manifestation of this is skylight—both its brightness and its bluish color. Without this scattering there would be no skylight. In its place, would be the dark night sky with the stars visible and a glaringly relentless sun.

As a consequence of the selective scattering and absorption of solar radiation, the spectral character and the intensity of sunlight varies with the altitude of the sun. When the sun is directly overhead its radiation is penetrating a single depth of atmosphere (air mass = 1). As it declines during the afternoon the air mass increases and the intensity of the short-wave ultraviolet particularly diminishes. A similar effect takes place as the sun declines in altitude with approaching winter. The latter also greatly effects the maximum hours of sunshine as indicated in Table I for the shortest and longest days in the year.

TABLE I

Maximum Daily Duration of Sunshine

Latitude	December 22		June 21	
0°	12h	07m	12h	07m
10°	11	32	12	43
20°	10	55	13	20
30°	10	13	14	05
40°	9	19	15	01
50°	8	04	16	23
60°	5	52	18	52
65°	3	34	22	03

The sun passes the equator between the dates corresponding to the longest and shortest days in the year at other latitudes.

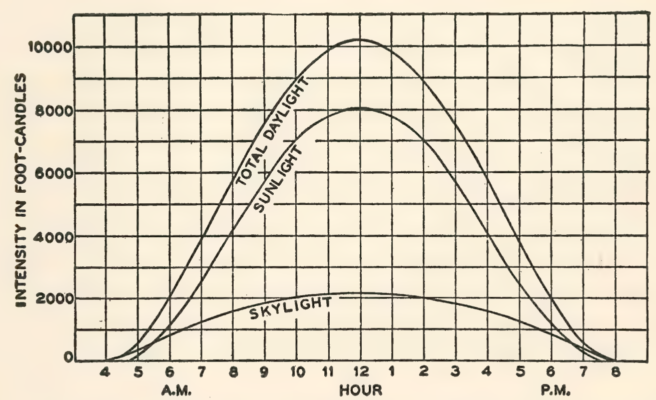

Fig. 2. Variation of skylight and sunlight on a horizontal surface throughout a typical clear day in midsummer.

At a latitude of 50° North the maximum duration of sunshine on June 21 is twice that on December 22. It is seen that there is a great variation during the year. Combining with this the seasonal variation in intensity and particularly in the quantity of important ultraviolet radiation we have such a great variation that it is not easy to define sunlight. With the daily and seasonal variation in quality and quantity of sunshine it is necessary for Nature to develop storage capacity in living things.

In Fig. 2 is represented the variation of skylight and direct sunlight (as measured with a photometer) on a horizontal surface throughout a clear cloudless day. If the direct sunlight is measured on a surface continually changed so that it is always perpendicular to the sun's rays, the variation is not as great throughout most of the day as it is on a horizontal surface. However, the variation of vital ultraviolet radiation is even greater than that indicated in Fig. 2 because of the increase of air-mass with decreasing altitude. The introduction of haze, smoke, and clouds further reduces the direct sunlight and causes extreme variations. Therefore, sunlight is extremely variable.

On clear days the maximum intensity of illumination due to direct sunlight is about 8000 footcandles and to combined sunlight and skylight it is as great as 10,000 footcandles. A day is considered dreary if the level of illumination outdoors is as low as 1000 footcandles. It is a "dark day" indeed when the intensity drops to 100 footcandles or less. However, in the indoor world in the daytime there are relatively few places illuminated to an intensity of 20 footcandles either by natural or artificial light. This great discrepancy between the amount of light used in the artificial world as compared with that outdoors under which the eyes evolved is appreciated by relatively few users of eyes. The low-intensity lighting indoors is responsible for much eye trouble and the attendant inefficiency and disorders. It is gradually being increased in lighting for seeing. However, in the production and utilization of artificial sunlight this discrepancy must be taken into account at the outset so that the biological effectiveness is adequate at the relatively much lower levels of illumination in use indoors.

The spectral transmission of average clear atmosphere (air mass = 1) is illustrated in Fig. 3. The data for the long wavelengths are chiefly those of Abbot [6] and for the short wavelengths are from Fabry and Buisson.[7] The energy distribution in the ultraviolet region of the solar spectrum is shown in Fig. 4 from data collected by Forsythe.[4] These curves are the basis of interesting computations discussed later.

The solar spectrum extends from approximately λ2900 (Angström units) in the ultraviolet far into the infrared region. Dependable measurements of infrared have been made with

the bolometer and thermopile to the region of λ55000 (5.5μ) and radiation is detectable to λ200000 (20μ). The amount of infrared radiation varies greatly with the quantity of water-vapor in the atmosphere, the average value being about two per cent in volume. The range is approximately equivalent to a layer of water up to a thickness of an inch. The infrared in solar radiation is of some importance as is shown later. However, the ultraviolet radiation near the short-wave end of the solar spectrum is of vital interest. Therefore, the short-wave limit has assumed great importance. (See Plate I.)

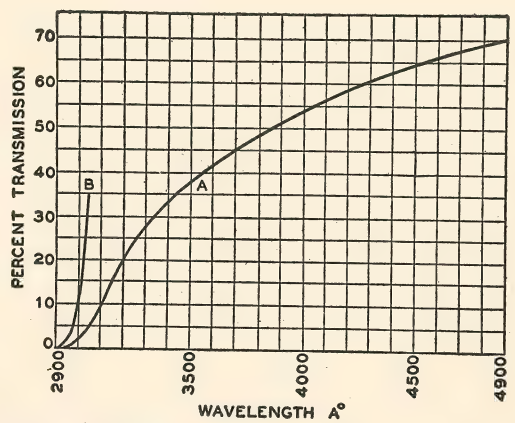

Fig. 3. Spectral transmission of a standard clear atmosphere. B equals 10 times A.

Although the limit of the solar spectrum is generally specified as λ2900, very little radiation of this wavelength reaches the earth's surface.[2] This may be considered the absolute limit. In most places there is little energy shorter than λ2950 and when the sun is low in winter or in smoky cities λ3100 is sometimes the limit. The maximum of erythemal effectiveness is approximately at λ2970 and the maximum antirachitic effectiveness seems to be somewhere between the limits λ2970 and λ3020. There is some evidence that the most effective energy in producing vitamin D by irradiating ergosterol is in the region of λ2800. Inasmuch

as the energy in the solar spectrum decreases very rapidly from λ3100 to the actual limit, it is seen that sunlight depends upon an enormous intensity of total radiation for its biological effectiveness in these respects.

On a cloudless day at places where the atmosphere is quite clear, if the practical limit of the solar spectrum at noon is at λ2950 it will gradually recede as the sun declines until near sunset it is likely to be well beyond the biologically-effective region. For example, it will be approximately at λ2950 for about three hours during midday in summer receding to λ2970 at 2:30 P.M., to λ3000 at 3:30 P.M., and to λ3100 at 4:30 P.M. The short-wave limit alters very little with altitude when the atmosphere is reasonably free from impurities. For example, Miethe and Lehmann found that the limit of the faintest trace of photographic action was at λ2913 at sea-level and that the limit remained practically unchanged to an altitude of about three miles, which was as high as they investigated. Of course, in a smoky atmosphere the short-wave limit is at a longer wavelength at sea-level. Inasmuch as the haze due to dust and smoke is usually carried upward by diurnal convection currents to an altitude of a mile there should be a more or less abrupt lengthening of the solar spectrum above this ocean of haze which is so obvious as viewed just above its upper surface. Depths of atmosphere encountered in ordinary lighting conditions do not appreciably absorb the ultraviolet radiations longer than λ2200. Beyond this the absorption increases as the wavelength decreases until in the neighborhood of λ1850 the absorption of air becomes very great. This energy largely disappears in the production of ozone and the process can be detected by the characteristic odor of this product.

The short-wave limit of skylight does not differ much from that of direct sunlight but it has a higher percentage of ultraviolet radiation than is generally appreciated. However, the relatively lower intensity of illumination contributed by skylight (Fig. 2) compared with direct sunlight usually eliminates it from consideration. However, long exposures to

midsummer skylight and sunlight reflected from clouds are certainly biologically effective. The short-wave limit of skylight varies seasonally as that of sunlight. In the vicinity of a large city it varied from λ2970 in midsummer to λ3070 in midwinter. In spring and fall the limit was generally not less than about λ3000.

In developing any subject involving the correlation of data from a new viewpoint the value of standardization of units and the opportunity for contributing toward orderliness are impressive. In the present case it is also difficult owing to usage and careless or practical modification of terms from their strictly accurate meaning. For example, throughout this text and general usage the words energy, radiant energy and radiation sometimes mean the same thing—a form of energy. At other times the term energy is used where intensity of energy is meant. Again energy is employed where rate of flow of energy—radiant power—is actually meant. No guarantee is made that the terms used herein are always strictly consistent but there should be no confusion as to their meaning under the conditions used.

Before entering upon a consideration of energy, energy intensities, radiant power, etc., let us view certain equivalents and their meanings. It appears most practical to compare units and equivalents on the basis of intensities of energy (radiant) operating for a unit of time on a unit of area. Actually, this is radiant power. To convert these power equivalents into energy equivalents it is necessary only to consider the power operating for a unit time. Of course, radiant power being a shower of radiant energy (commonly termed energy or radiation for brevity) over an undefined area, it is necessary to introduce a unit area (a sq. cm.) upon which the mind is focused or measurements are made. The radiant power absorbed by this square centimeter of surface (perpendicular to the direction of the flow of energy) in a unit of time is a measure of the total energy absorbed.

With these considerations the following power equivalents are listed:

1 millicalory per minute per sq. cm.
0.001 gram-calory per minute per sq. cm.
0.07 milliwatts per sq. cm.
70 microwatts per sq. cm.
700 ergs per sq. cm. per sec.
700 watts $\times 10^{-7}$ per sq. cm.
7 watts $\times 10^{-7}$ per sq. mm.

It is convenient to express biologically-active ultraviolet radiation in sunlight as radiant power in terms of microwatts per sq. cm. and the total solar radiation as radiant power in terms of milliwatts per sq. cm. This is evident when one considers the magnitudes of radiant power in the paragraphs which follow.

The limiting wavelengths of ultraviolet radiation of known biological value are not well known. Therefore, it is difficult to establish absolute values of radiant power or the energy-flow necessary for biological effect by analysis of sunlight. Furthermore, it presses non-selective energy-measuring instruments to the limit of sensibility to obtain reliable data. In fact, data of unquestioned high accuracy pertaining to the short-wave ultraviolet in sunlight or in artificial illuminations are very rare. Coblentz, whose experience has extended over many years during which he has contributed a great amount of valuable data, has studied the ultraviolet region extensively. He and Stair [3] obtained values of the percentage of solar radiation between λ2950 and λ3100 in the total radiation reaching sea-level (Washington, D. C.) through one atmosphere (air-mass = 1). The values by four different methods vary from 0.04 per cent to 0.6 per cent, the average being 0.3 per cent. Inasmuch as the total incident solar radiation (considered as power or energy-flow) is 1.2 to 1.4 gram-calories per square centimeter per minute, 0.3 per cent of this is about 0.004 gr. cal. per sq. cm. per minute. By the method which measured the radiation shut out by a filter of common glass they found that the amount of ultraviolet radiation which would not pass through a glass filter, varied from about 0.001 gr. cal. per sq. cm. per min. in

winter to about 0.007 in summer or, respectively, 600 and 5000 ergs per sq. cm. per second.

Dr. Janet Clark, at Baltimore, using the rate of blackening of zinc sulphide, obtained values of the same range and magnitude, 500 ergs in winter and 4000 ergs per sq. cm. per second in summer, which are in good agreement with Coblentz.

Using data available (Figs. 3 and 4) Forsythe and Chris-

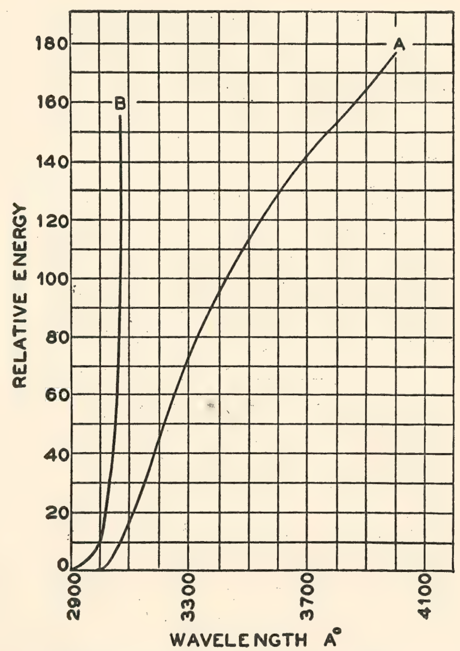

FIG. 4. Energy distribution in the ultraviolet region of the solar spectrum. B equals 10 times A.

tison[4] computed the radiant power between $\lambda 2900$ and $\lambda 3100$ for solar radiation and obtained 0.024 milliwatts per sq. cm. for one atmosphere thickness and an almost negligible quantity, 0.00017 milliwatts per sq. cm., for 2.37 atmospheres in midwinter at the latitude of Cleveland. For conditions corresponding to midsummer their computations indicated 0.02 milliwatts per sq. cm. or 200 ergs per sq. cm. per second. These computed values are radically different from the ob-

served values presented in the preceding paragraph, but the difference is readily explainable.

Greider and Downes[5] determined the spectral energy distribution of sunlight in October in Ohio and in November in Colorado. They found the energy-flow or radiant power between $\lambda 2900$ and $\lambda 3100$ to be 1.2 and 1.6 watts $\times 10^{-7}$ per sq. mm. in the two locations, respectively. The average value of 1.4 watts $\times 10^{-7}$ per sq. mm. is equivalent to 140 ergs per sq. cm. per second or 0.014 milliwatts per sq. cm. These values were obtained approximately midway between summer and winter. According to the computations of Forsythe and

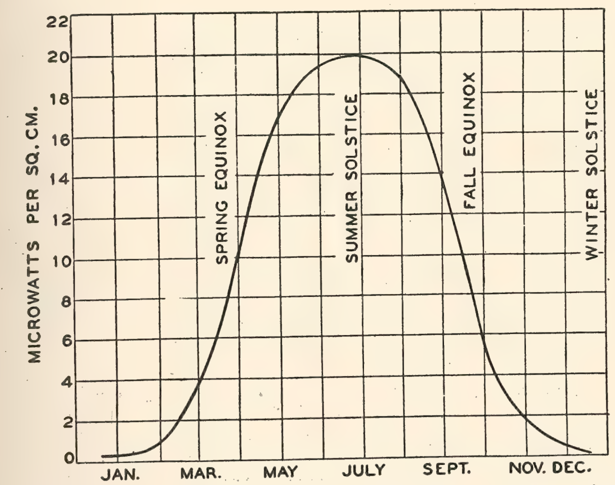

FIG. 5. Results of computations of solar ultraviolet energy in microwatts per sq. cm. between $\lambda 2900$ and $\lambda 3100$ by Forsythe and Christison using data of Abbot and of Fabry and Buisson.

Christison (Fig. 5) they should be multiplied by about 3 to represent midsummer. This would bring the average value to about 420 ergs per sq. cm. per second or 0.042 milliwatts per sq. cm. for midsummer sunlight. According to the observations of Coblentz and Stair the values obtained by Greider and Downes should be multiplied by about 2.5 to bring them to midsummer values. This would make their average value for midsummer sunlight 350 ergs per sq. cm. per second or 0.035 milliwatts per sq. cm.

To return to the measurements and computations of the energy in sunlight between λ2900 and λ3100 and measurements of these which are merely estimates, let us consider the summary in Table II expressed in microwatts per sq. cm. These values multiplied by 10 give ergs per sq. cm. per second. From data pertaining to the production of erythema by means of tungsten filaments in ultraviolet-transmitting bulbs, we obtained, as shown in Chapter X, a value of 40 microwatts per sq. cm. for midsummer midday solar radiation shorter than λ3100. Our results indicate that this value is not likely to be exceeded very often in the latitudes of the temperate zones. Furthermore, our results indicate that this value for midday summer sunlight on a clear day can scarcely be less than 24 microwatts per sq. cm. The former value was obtained by means of certain corrections which we applied. Without these corrections the latter value was obtained. Therefore, from our erythemal tests combined with computations we conclude that the true value for midday midsummer sunlight at the latitude of Cleveland on a clear day is between 25 and 50 microwatts per sq. cm. of radiation shorter than λ3100 and that 40 microwatts per sq. cm. seems to be a likely value.

TABLE II

COMPUTED MAXIMUM ENERGY, BETWEEN λ2900 AND λ3100 IN NORMALLY INCIDENT SOLAR RADIATION AT SEA-LEVEL, EXPRESSED IN MICROWATTS PER SQUARE CENTIMETER PER SECOND

Coblentz and Stair	35
Pettit [8]	70
Forsythe and Christison	20

VALUES MEASURED BY VARIOUS MEANS

	Summer	Spring Fall	Winter
Coblentz and Stair			
Component not transmitted by common window-glass	500	(230)	60
Dr. Janet Clark			
Blackening of zinc sulphide	400	....	50
Greider and Downes			
Spectral Energy Measurements	..	14	..
Multiplied by 3	(42)	....	..
Multiplied by 2.5	(35)	....	..
Luckiesh			
Erythemal method	40	....	..

The variation among the computed values is not serious. If thoroughly reliable energy measurements were available or easy to make, computations would not be resorted to. On the other hand, in computing spectral components it is necessary to use, as a foundation, measurements of the spectral energy in solar radiation and of the spectral transmission of the atmosphere. Therefore, they include any errors of the data obtained by measurement. Forsythe and Christison used data published by Abbot [6] for the spectral transmission of the atmosphere and the distribution of energy in the solar spectrum. This was supplemented by the data of Fabry and Buisson.[7] Coblentz and Stair used Abbot's data with some modification. The computations are straightforward and simple so that they introduce no difficulty. Doubtless, the variation in the computed values in Table II is due largely to the abruptness of the ending of the solar spectrum. A slight difference in the slope of the curves makes a large difference in the integrated value.

The average of the computed values of the maximum amount of solar energy between λ2900 and λ3100 is about 42 microwatts per sq. cm. If the data of Greider and Downes multiplied by 3 (a factor taken from Fig. 5) are included, the average remains the same. These values are only one-tenth those obtained by the methods of Coblentz and of Clark. Inasmuch as the computed value between λ2900 and λ3250 is ten times that between λ2900 and λ3100 it is logical to suspect that the experimental methods of Coblentz and of Clark included considerable energy longer than λ3100. This is to be expected from a glass filter which has a cutoff at λ3100 because the spectral-transmission curve slopes more or less as it approaches the practical cutoff instead of ending perpendicularly or abruptly. The same analysis applies to a photochemical reaction such as the blackening of zinc sulphide. From a biological viewpoint it may be found that the conclusions of Coblentz and Stair and also of Clark appraise sunlight as well as the computed values between λ2900 and

λ3100. This can be settled only by careful investigations of biological effectiveness.

Coblentz and Stair used a filter (Corning G 986A) to isolate the ultraviolet region and then determined the radiant power which was not transmitted by window-glass, using proper precautions to eliminate infrared by means of a water-cell. The spectral cutoff of the window-glass is not sharp for no transmission-filters possess this characteristic. An advantage of this method is that, in a sense, it greatly magnifies the component not admitted by the window-glass filter compared with the total radiation measured. The data obtained are very useful in many ways but the partition or cutoff in the spectrum cannot be specified in terms of a single wavelength. The data are unquestionably accurate but they cannot be considered limited to λ2900 and λ3100 because of the indeterminate long-wave limit. (See Table XXXVI, Chapter XIII.)

The apparent discrepancy between the computed and observed results in Table II is not serious. The observed values may be as near to the biological truth as the computed ones. The values are not for exactly the same energy range. At least we gain from these data the order of magnitude of the vital ultraviolet energy in sunlight. The large factors of safety, common in Nature and in life-processes, do not require great accuracy in the quantity of radiation as long as it is above threshold value. Beyond such values the photochemical processes are commonly wasteful. It is likely that the lowest value in Table II is quite adequate for most of Nature's needs and that the highest value is equally satisfactory. In the development and use of artificial sunlight there will be great variations in duration of exposure and in intensity of radiation. We shall need absolute energy and power measurements and also standard units but, as the author has already suggested, the footcandle will still remain a very convenient and satisfactory measurement. The biological effectiveness per footcandle will be determined. In fact, we have already related erythemal effectiveness to footcandles for several sources over a wide range of exposures which may be used in new-era lighting. Energy measurements are valuable and necessary but they are meaningless biologically until appraised in terms of biological effects. Neither the data nor the discrepancies in Table II are to be taken too seriously from the viewpoint of the objective of this book because the energy between λ2900 and λ3100 is neither uniform in the solar spectrum nor is it of uniform biological effectiveness. The spectral antirachitic effectiveness and the spectral erythemal effectiveness have their maxima somewhere in this region but the effectiveness in each case decreases rapidly both ways from the maximum. Also, there is some evidence that the maximal effectiveness of radiation in the production of vitamin D in ergosterol is outside the solar spectrum—near λ2800. In any event it is easy to improve upon sunlight by producing a relatively much greater percentage of radiation between λ2800 and λ3100 than is present in sunlight. In fact, this must be done if an artificial sunlight is to be successful.

The spectrum of artificial sunlight can be extended as far into the ultraviolet as is safe for the eyes; that is, without causing conjunctivitis. A safe limit appears to be at λ2800 or slightly less considering the exposures and intensities involved. Also it may be found that energy longer than λ3100 is desirable. The computations of Forsythe and Christison indicate that there is ten times more energy in solar radiation between λ2900 and λ3250 than between λ2900 and λ3100. Their computations also indicate that on cloudless days for five or six hours the energy in each of these two regions does not fall below half the value at noon; that is, the energy shorter than λ3250 is above half its maximum value from 9:00 A.M to 3:00 P.M. The energy shorter than λ3100 is greater than half its maximum value from 9:30 A.M. to 2:30 P.M. However, it is difficult to believe that the biological effectiveness of solar radiation through clear atmosphere in midwinter is as negligible as their computations indicate.

The difficulty of answering the question, What is sunlight? is obvious in the foregoing pages. We had to answer a similar question years ago in developing artificial sunlight for the

discrimination of color. But in that work we had two "standards" at least—noon sunlight, which is approximately colorless, and north skylight which had been adopted because it was the least variable in intensity. Besides, we had only one photochemical reaction to deal with—the visual process. In the development of artificial sunlight we have several inadequately known photochemical reactions and much more variable spectral energy—in the extreme ultraviolet portion of the solar spectrum. The known biological effectiveness of solar radiation varies enormously with the sun's altitude daily and seasonally and with atmospheric conditions. Whether to use the maximum value of ultraviolet radiation known to be desirable or whether to use the average are questions which seem to bother some. As a matter of fact, the spectral energy values in sunlight will serve only as compasses, not as anchors.

The conditions in indoor lighting are so radically different from those outdoors in the daytime that great modifications must be made in artificial sunlight to meet the new situation indoors. Fortunately, Nature's factors of safety greatly reduce the difficulty of the task. As is shown in later chapters an entirely different procedure, not involving energy measurements, is practicable. A safe spectral limit and suberythemal exposures, with safe intensities over long periods, are of primary importance. These can be determined for any source and the source modified to suit. All the knowledge of solar radiation obtainable will be useful but we have sufficient data to proceed without difficulty to improve upon it.

Solar radiation is of interest owing to its heating effect and to the radiation of those wavelengths which penetrate the bodily tissue. Stimulation of normal processes, such as the flow of blood and perspiration, are certainly without harm to healthy persons and are often considered helpful to those who are ill. Besides this effect, the warmth is relaxing as a hot bath. The maximum energy-flow of solar radiation at sea-level averages about 1.3 gram-calories per sq. cm. per minute in middle latitudes. This is about 91 milliwatts or 91000 microwatts per sq. cm.

The long-wave visible and the short-wave infrared radiation penetrate the bodily tissue and heat it at a depth. The apparent- or color-temperature of the sun is almost ideal as a source of energy which penetrates the bodily tissue. The energy from $\lambda 6300$ to $\lambda 14000$ penetrates water, flesh and blood quite effectively. Energy from $\lambda 14000$ to $\lambda 80000$ is absorbed by a layer of water an inch or less in thickness. This range covers the long-wave end of the solar spectrum so that only the range from $\lambda 6300$ to $\lambda 14000$ is of interest in penetrating the bodily tissue to a depth. About one-third of the total solar radiation is in this spectral range. (See Table VI.)

Although the viewpoint of this book is particularly directed toward the health-maintaining value of radiant energy in addition to lighting for vision, new data pertaining to daylight as the eyes use it are of interest. The color of daylight including sunlight and skylight separate and combined has been determined by A. H. Taylor,[9] a colleague in the development of artificial-daylighting. Of course, color-temperature cannot serve as a guide to spectral composition of light without certain other knowledge. However, with such knowledge color-temperature data are very valuable.

Since the spectral composition of sunlight in the visible spectrum approximately obeys certain well-established laws governing the radiation from a so-called black-body, the most satisfactory method of describing daylight, as the eye appraises it, is to assign to it the temperature of a black-body whose light is of the same color. Even the color of skylight, and of mixtures of it with direct sunlight, can be approximately expressed in color-temperatures. Hence, it is possible to color-match various phases of daylight with artificial light having approximate black-body distribution of energy, and by this means assign color-temperature values to daylight without complete knowledge of its spectral distribution of energy. However, the latter must be reproduced if an artificial daylight is to be satisfactorily equivalent.

In Fig. 6 the solid line represents the spectral energy distribution of a black-body radiator at 5600 deg. K. The

circles are Abbot's data for noon sunlight in Washington, D. C., averaged for the summer and winter solstices. These circles and the black-body curve are so plotted that the total luminosity is equal in the two cases. Therefore, this average noon sunlight has a color-temperature of 5600 deg. K. With a specially constructed "daylight colorimeter" Taylor determined the color-temperatures of a wide variety of daylights throughout the season. A summary of the results is presented in Table III as obtained on the roof of a building in suburban Cleveland at an altitude of 840 feet above sea-level.

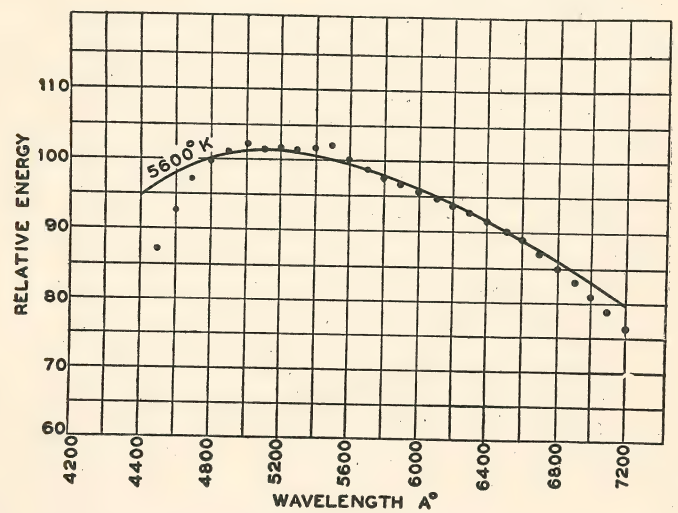

FIG. 6. Spectral energy distribution of a black-body radiator at 5600 deg. K. The circles represent Abbot's data for average noon sunlight on a clear day in Washington, D. C.

Fig. 7 brings out more clearly the significance of these color-temperature values. This illustrates the black-body distribution of energy corresponding to typical cases shown in the table. The method of evaluating color-temperatures is not very sensitive in the higher range of clear skylight colors. On one or two very clear days apparent color-temperatures of 35000 and 50000 deg. K, as evaluated by this method, were encountered for skylight.

Table III shows that when the direct sunlight is unobstructed from a horizontal surface, the color of the daylight received between 9 A.M. and 3 P.M. varies between the values of 5900 deg. K and 6900 deg. K, depending upon the degree of cloudiness, haze, etc. If the direct sunlight is screened off, the color-temperature may vary between 6700 and 26000 deg. K. This condition represents approximately the case of a room receiving light from a window with no direct sunlight entering. Therefore, light from a diffusing "skylight" receiving sunlight all day (as well as light from the sky) will generally be more constant in quality than that of a north window which has erroneously been considered to give day-

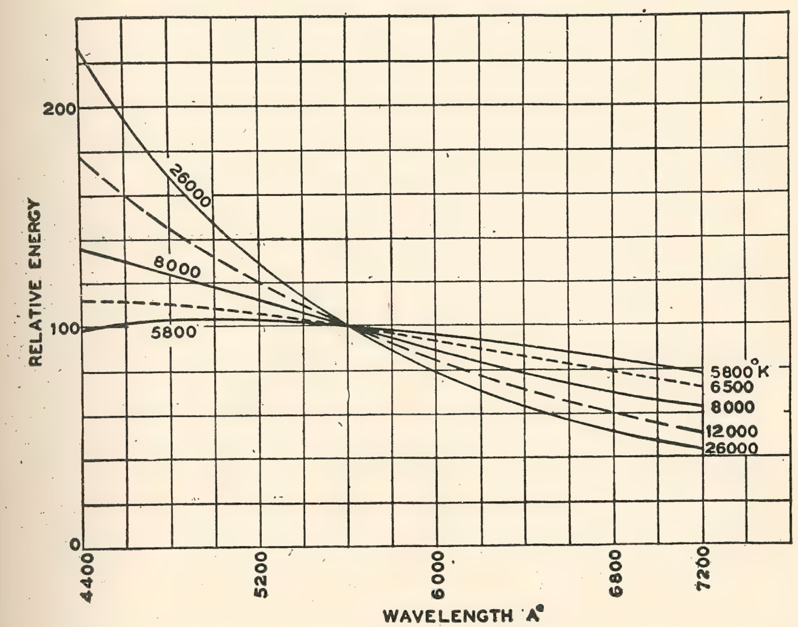

FIG. 7. Spectral energy distribution corresponding to five black-body temperatures, approximately representing five different phases of daylight or mixtures of sunlight and skylight. (See Table III.)

light most constant in quality. Of course the variations in quantity due to passing clouds and to the changing angle of incidence of sunlight would be troublesome in accurate color discrimination.

TABLE III

AVERAGE COLOR-TEMPERATURES OF DAYLIGHT FOR VARIOUS SEASONS AND WEATHER CONDITIONS (LIGHT RECEIVED ON A HORIZONTAL PLANE)
(A. H. Taylor)

	April and May	June and July	Sept. and Oct.	Nov., Dec. and Feb.
Direct sunlight alone, 9 A.M. to 3 P.M.	5800°K	5800°K	5450°K	*5500°K
Direct sunlight before 9 and after 3	5400	5600	4900	*5000
Sunlight plus light from clear sky 9 A.M. to 3 P.M.	6500	6500	6100	*6200
Before 9, after 3	6100	6200	5900	*5700
Sunlight plus light from a hazy or slightly overcast sky	5900	5800	5900	5700
Sunlight plus light from 25 per cent to 75 per cent overcast sky	6450	6700	6250	....
Totally overcast skylight	6700	6950	6750	....
Light from hazy or smoky sky	7500	8150	*8400	7700
Light from clear blue sky 9 A.M. to 3 P.M.	26000	14000	12000	*12000
Before 9, after 3	27000	....	....	12000

* One observation.

Unfortunately, color-temperature measurements cannot be extended by computation into the ultraviolet region of the solar spectrum. They are very helpful in computing ultraviolet energy from solid radiators such as carbon and tungsten filaments. Owing to the selective absorption of the atmosphere, color-temperature even fails as a foundation for spectral analysis of daylight in the violet region as seen in Fig. 6.

The foregoing paragraphs are a brief summary covering the various features of solar radiation in an attempt to indicate what it is. At least it has been shown that it is extremely variable. Artificial sunlight must be developed more or less independently of natural sunlight. The spectral limit, the intensity, the color and the various kinds of biological effectiveness are sufficiently known to serve as guides. Little more is needed because man's indoor world is so artificial, so greatly different in certain important factors. The sun's beneficence is being brought indoors and conditions require an artificial sunlight radically different in some physical respects. Herein lies the opportunity for originality and ingenuity.

CHAPTER IV

EFFECTS OF SPECTRAL ENERGY

Throughout the universe radiant energy of a vast range in wavelengths or frequencies is being sent forth by atoms and stars. Atoms and even their environments are distinguished by the spectral energy which they emit. They are recognized almost as easily in far-off stars as in the laboratory. In fact, the stellar laboratories, providing environments as yet unproducible by man, have been of great assistance in the study of the constitution of matter. Investigators in physical sciences began the study of matter long ago and, as they reflected and experimented, matter—in the old sense of substance—disappeared. It changed into energy which apparently is both the spirit and substance of matter. Thus, knowledge seems to have dissolved the material universe into an ethereal something which is eternal, fundamental, primordial. Secrets of life-processes seem less deeply hidden and mind loses some of its awesome mystery as matter loses its old-fashioned substance or materialism.

The earth is bathed in the energy-flow from the sun, myriad atoms and stars but apparently solar radiation as strained through the atmosphere is overwhelmingly important. The entire gamut of wavelengths or frequencies of radiant energy which have been studied is illustrated in Fig. 8. The scale of wavelengths is logarithmic in order that this great range may be more conveniently shown in a single chart. Each division of the scale represents a wavelength one-tenth that of the division immediately below it. There is a tendency to designate radiant energy in frequencies (the reciprocals of wavelengths) and there are substantial practical and fundamental reasons for doing so. However, our present purpose is better

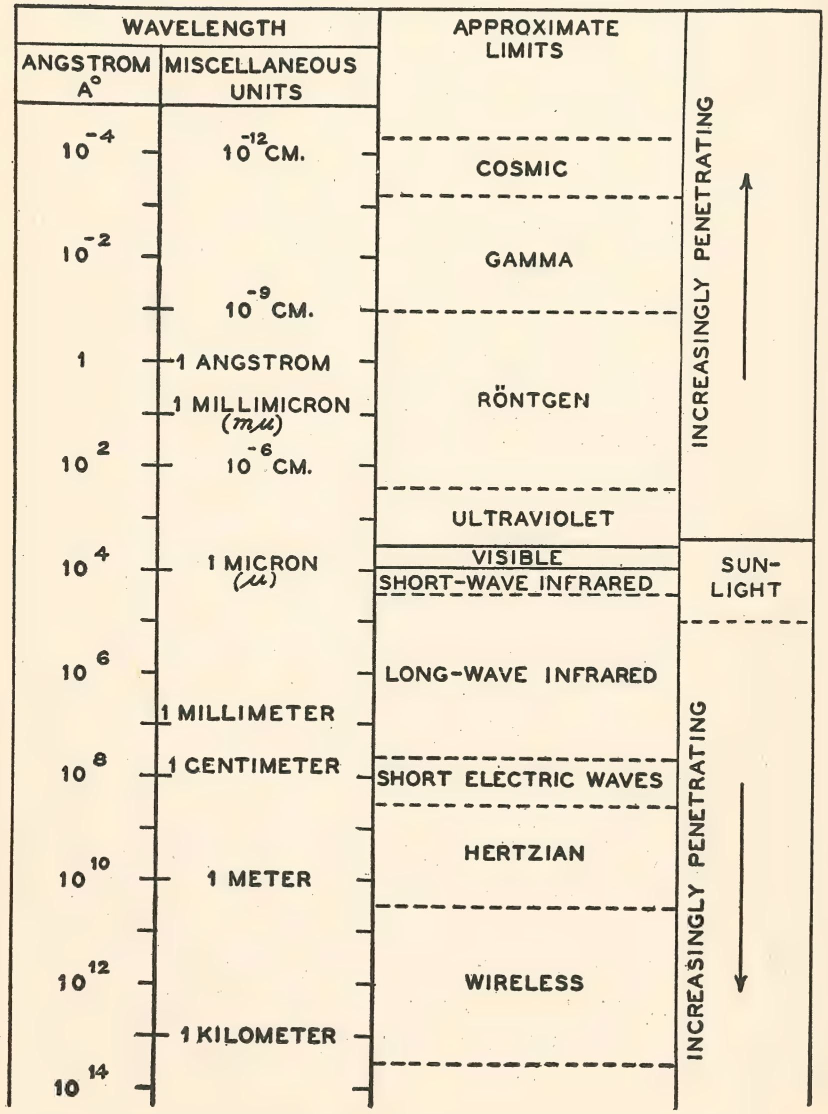

FIG. 8. The entire gamut of spectral energy which has been studied from both natural and artificial sources. The wavelength scale is logarithmic.

served by adhering to the more generally known designation —wavelengths. It is seen that solar radiation at the earth's surface constitutes a small range in the entire known scale of natural and artificially produced radiant energy.

Comparing the spectrum of the solar energy, under which life on earth evolved, with the total gamut one is impressed by the fact that it lies in the region of general absorption by most materials. The radiant energy represented toward the top and the bottom of the chart becomes increasingly penetrating as the wavelength decreases or increases, respectively. Certainly, cosmic rays are highly penetrating. Substances are more generally transparent to gamma and Röntgen rays than to ultraviolet, visible, and infrared radiation. Toward the lower end of the scale the increasing penetrability is not as pronounced as toward the upper end. Nevertheless, solar radiation is the region of less penetrability. This is more than accidental. Energy must be absorbed to be utilized. Absorption converts it into heat energy, chemical energy, mechanical energy, electrical energy, and perhaps into forms unknown. Life-processes of living things at the earth's surface evolved under vibrational radiant energy. "Vibrant with life" is more than a poetical phrase. Throughout Nature from inorganic atoms to complex organic processes periodicity is interwoven. Living things must absorb solar energy in order to utilize it. There are myriad reactions in myriad living things. It is not surprising that at least some have developed the ability to use —and, therefore, to need—certain spectral energies. That Nature is vibrant and bathed with radiation of generally low penetrability is not surprising.

Evolution is the change of characteristics. The natural process is very slow measured by units of time most important to man. Contrasted with the lifetime of human beings and with their achievements in forced selection, Nature is slow and inefficient. But with time available in infinite abundance, the hands on Nature's time-clock are practically motionless. Evolutionary changes which require millions of years on our calendar are not even a tick of the cosmical clock. However, our

time-piece is valuable because it separates changes and events so that we may gain a picture of the details and, therefore, of the whole. We see evolution as a gradual and continual process—a cosmical metabolism. To us it is a slow-motion picture which enables us to see the varying rate of rise and fall of order and species. We even detect the differences in individuals which aid evolution or make it possible. A study of living things reveals differences which multiply until there is danger of seeing Nature as a disorganized competition of living things. More intimate views reveal the whole of life

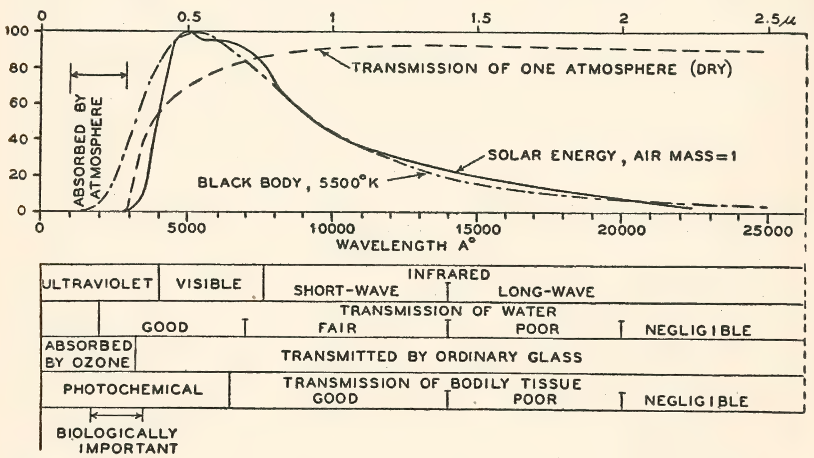

FIG. 9. The spectral range corresponding to the practical limits of the solar spectrum and in addition the ultraviolet radiation not transmitted by the atmosphere.

as a sort of organism developing upward. Extending the horizon adds to the picture the eternal motions within the atoms and among the stars. Energetic matter enters in the rôle of energizing natural processes, to what importance and end none can say. The ways of natural evolution do not always appear to be wholly accountable by environment. Knowledge in this direction is fragmentary. However, environment must be the all-important factor in the so-called material universe; and, therefore, radiant energy becomes an important part in this scheme.

Besides the entire gamut of wavelengths presented in Fig.

8, several succeeding illustrations deal with lesser spectral ranges of energy.

Fig. 9 is confined to the range of the solar spectrum plus the ultraviolet range of atmospheric absorption. The color-temperature of sunlight at the earth's surface corresponds approximately to that of a black-body at about 5500 deg. K. Taylor's recent measurements, as seen in Table III and Fig. 6, indicate that the color-temperature of midday midsummer sunlight (for the visible spectrum) is 5800 deg. K and in spring and fall is about 5450 deg. K. During midmorning and midafternoon the color-temperature of direct sunlight is about

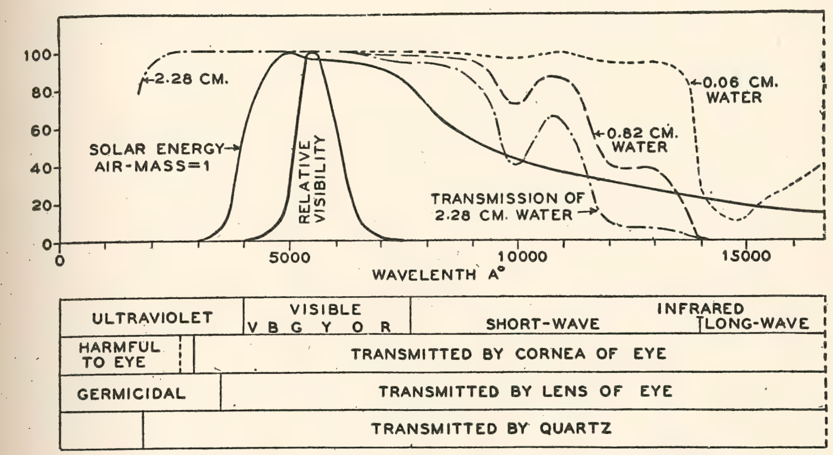

FIG. 10. The spectral range of most immediate importance to human beings.

5450 deg. K in midsummer and in spring and fall averages about 5250 deg. K. With skylight added to direct sunlight these values are about 800 deg. K higher, midday midsummer daylight (sunlight plus skylight on a clear day) having a color-temperature of 6500 deg. K. In Fig. 9 the spectral distribution of energy from a black-body at 5600 deg. K. has been plotted as being sufficiently close to that of solar radiation at the earth's surface for the present purpose. The regions of different degrees of transparency of water and bodily tissue are indicated approximately.

In Fig. 10 the spectral range of most immediate impor-

tance to human beings is presented with several prominent characteristics, such as visibility of radiant energy between λ3900 and λ7600 and the spectral transmission of various thicknesses of water.

The ultraviolet range is treated in Fig. 11 with some of the important features indicated. All spectral ranges must be investigated further in regard to their influence upon life and health but ultraviolet radiation is of particular interest.

The erythemal range as well as is known at present extends chiefly from λ3100 to λ2800 with a maximum at about λ2970. There is no necessary connection between erythema and beneficial effect of radiant energy but inasmuch as biologically-

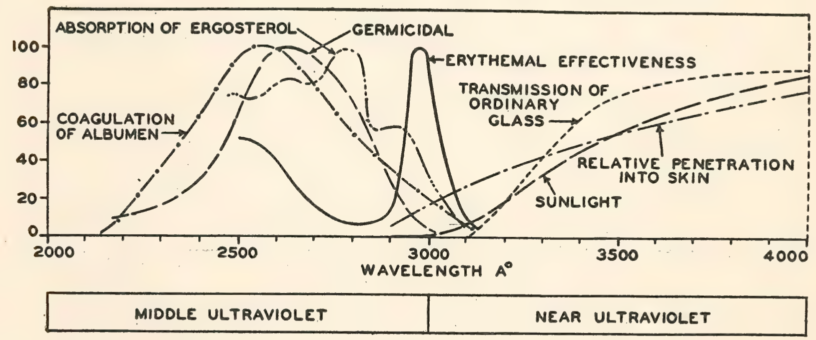

FIG. 11. Important spectral data pertaining to ultraviolet radiation.

active rays are in the same region of the spectrum erythema must be reckoned with. The spectral antirachitic effectiveness is not known excepting for its approximate long-wave limit which is certainly shorter than λ3200 and possibly at about λ3100. Nevertheless the antirachitic maximum is near λ3000 and, therefore, is intimately associated with erythema in considerations of the physics of radiation.

The spectral erythemal effectiveness obtained by us and Hausser and Vahle[13] is presented in Fig. 12. Owing to the extreme difficulties involved in making these determinations it is natural to consider that they are only approximately correct. The solid curve represents results published in 1922 and the

broken curve those published in 1927. Apparently the maximum is well established. If one knows the spectral distribution of energy for any source, the energy values may be multiplied by the erythema values for corresponding wavelengths. By integrating the area underneath the resulting curve relative

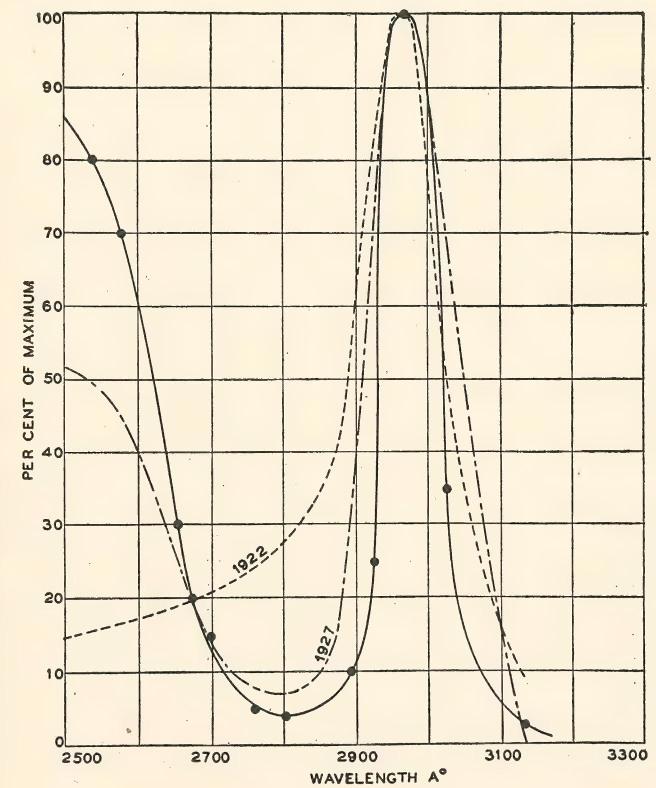

FIG. 12. The spectral erythemal effectiveness of radiation as determined by Hausser and Vahle in 1922 and 1927 is shown in the broken curves. The unbroken curve with black circles is a recent determination by the author and colleagues. (See Table IV.)

erythemal effectiveness can be obtained for the source. In this manner interesting comparisons can be made. In Table IV the values of erythemal effectiveness relative to the maximum are presented for various wavelengths. We have made such computational comparisons more as a rough appraisal of spectral

energy data. We prefer to rely upon actual erythemal determinations in laying the foundation for artificial sunlight until essential data become thoroughly established.

The author and his colleagues, A. H. Taylor and L. L. Holladay, have determined the erythemal effectiveness of equal amounts of energy of various wavelengths upon untanned skin. The average values for three persons, presented in Table IV, agree fairly well with the later determinations of Hausser and Vahle.

Beginning with the surface of the skin the principal layers at increasing depths are:

1. The horny layer (corneum)
2. The basal cells (stratum granulosum)
3. Network of blood-vessels (rete vasculosum)
4. Corium
5. Subcutaneous tissues.

TABLE IV

Relative Erythemal Effectiveness of Energy of Various Wavelengths in Terms of the Maximum
(Hausser and Vahle)

Wavelength	1922	1927
3132	4.5	0
3024	58.0	70
2967	100.0	100
2894	30.0	33
2804	28.0	7
2654	19.0	25
2537	16.0	50

(Luckiesh, Taylor and Holladay)

Wavelength	Erythemal Effectiveness	Wavelength	Erythemal Effectiveness
3663	0	2760	5
3342	0	2700	15
3132	2.5	2675	20
3024	35	2654	30
2967	100	2576	70
2925	25	2537	80
2894	10	2482	90
2804	4	2399	95

Although data pertaining to the penetration of ultraviolet energy into the skin are somewhat meager and conflicting, a sketchy picture for certain spectral ranges is as follows:

λ2000 to λ3200 readily kills surface organisms.
λ2000 to λ2500 penetrates to horny layer and possesses moderate erythemal power.
λ2500 to λ2800 penetrates basal cells, produces some pigment, and possesses moderate erythemal power.
λ2800 to λ3200 penetrates blood-vessel network, producing considerable pigment and erythema, stimulating sweat glands and sympathetic nerves.
λ3200 to λ3900 penetrates corium and differs from preceding spectral range in degree of effects.
λ3900 to λ14000 penetrates and heats subcutaneous tissues.

TABLE V

Percentages of Energy of Various Wavelengths Which Pass Through Skin of Different Thicknesses in Millimeters
(Hasselbach)

	Per Cent Transmitted (Thickness of Skin)		
Wavelength	0.1 mm.	0.5 mm.	1.0 mm.
4359	59	7	0.5
4050	55	5	0.3
3663	49	3	0.08
3342	42	1.3	0.02
3132	30	0.3	0.008
3024	8	..	....
2967	2	..	....
2894	0.01	..	....

Percentages of Energy of Various Wavelengths Reflected by Untanned Skin
(Luckiesh, Taylor and Holladay)

Wavelength	Per Cent Reflected	Wavelength	Per Cent Reflected
2400	3	3600	21
2600	3	4000	28
2800	3	4500	35
3000	4	5000	42
3200	11	5500	48
3400	17	6000	54

The absorption of ultraviolet energy by the skin rapidly increases as the wavelengths decrease beyond λ3200. According to some researches it becomes very high for λ2800 and shorter wavelengths. In contrast with visible and short-wave infrared radiation which readily penetrates bodily tissue to depths of several centimeters, ultraviolet radiation penetrates skin to a depth of about one millimeter or less. By pressing

skin tissue between quartz plates and illuminating with a quartz mercury arc it is possible to blacken photographic paper by ultraviolet energy transmitted through the skin. Such data are so difficult to obtain that there is little agreement among them. It is sufficient for the present purpose to know that the depth to which ultraviolet radiation penetrates the skin decreases as the wavelength decreases. Although 50 per cent of the energy at λ3660 may penetrate a depth of 0.1 mm. of skin only 2 per cent of the energy at λ2970 may penetrate to the same depth. These values are hundreds of times greater than the amounts which penetrate to a depth of 1 mm. Radiant energy of λ2800 and less probably penetrates to a maximum depth of no more than 0.1 mm.

The percentages of energy of various wavelengths which pass through various thicknesses of skin are presented in Table V as determined by Hasselbach.[14] These data may have serious limitations but at least they show the decreasing penetrability with decreasing wavelength. The short-wave ultraviolet does not penetrate the basal layer of the epidermis.

The percentages of energy of various wavelengths reflected by untanned skin, as determined by the author and his colleagues, are presented in Table V. These are averages for three different untanned normal skins.

Tanning, or the formation of pigment in the skin, is not thoroughly understood. Certainly, it cannot be taken as a measure of health. Ill persons confined indoors and unexposed to the sun possess a pallor associated with illness. Healthy persons exposing themselves more or less to the sun are pigmented or tanned to some extent. However, the degree of tan in itself is not a measure of health but usually accompanies it just as a golf-bag does. A good tan affords protection against over-exposure to ultraviolet radiation and apparently does not seriously reduce the known beneficial effectiveness of sunlight or of its artificial substitutes. Negro skins apparently have the power to produce pigment unaided by ultraviolet radiation. Albino skins do not have this power even with the aid of radiant energy. One theory is that two substances are needed to produce pigment and that negro skins unaided supply both to a marked degree although they can become tanned darker than normal by exposure to sunlight and, of course, they can develop erythema or sunburn. Albino skins aided by sunlight may be able to supply one of the two substances but not the other. Normal white skins may be between these two extremes, the skin supplying one substance unaided and producing the other with the aid of sunlight. Continuing this same theory it is possible to account for the difference in the degree of pigmentation caused by various wavelengths of ultraviolet radiation. Energy of λ2800 and shorter may not penetrate deeply enough in sufficient quantities to produce much of the substance requiring the aid of ultraviolet. Therefore, the production of pigment is less than for ultraviolet radiation of longer wavelengths. Solar radiation between λ3000 and λ3200 produces a rich brown pigment perhaps aided by the hyperemia and dilated blood capillaries. It does not seem that the latter effect can be left out of account in considering the production of pigmentation. Perhaps even this tide of blood leaves behind some of the blood pigment which has been wedged into the capillaries. However, the foregoing theory seems to have some firm basis of fact.

It is readily noted that for a given degree of erythema a quartz mercury arc (rich in erythemal radiation from λ2600 to λ3000) produces a lesser tan than sunlight which is correspondingly rich in radiation from λ3000 to λ3200. It is obvious that the spectral erythemal effectiveness is not the same as the spectral pigmenting effectiveness. Apparently erythema and pigmentation are not intimately or even closely related.

Depigmentation or loss of tan in the skins of whites after exposures to sunlight or its artificial substitutes takes place more or less slowly depending upon the initial degree of pigmentation. The cells in which pigment has been produced are unable to produce pigment without the aid of ultraviolet radiation. As the cells divide the new cells contain only one-half the pigment of the original cells. This process of subdivision proceeds with a mathematical fading of the tan. Some

of the cells die and they and their pigment are drained off. Other cells are pushed to the surface and are rubbed off and eventually the skin is free of pigment.

Other functions of pigmentation, aside from being a protection from the lethal action of sunlight, are not well known. It influences temperature of the body and temperature regulation. A dark skin radiates more heat than a white one and therefore aids in keeping the body cool when the surrounding air is at a temperature lower than that of the body. When the air is at a higher temperature than the body the dark skin is at a disadvantage. The entire question of pigmentation is a complex one and of insufficient importance from the viewpoint of this treatise to go into details.

In the development and use of artificial sunlight the safety of the eyes from the destructive action of radiant energy is very important. As a result of environment the human race has developed a partial immunity to injury of the eye by the ultraviolet radiation present in sunlight in summer. Under normal conditions our eyebrows and eyelashes protect us to a large extent from receiving excessive amounts of the abiotic radiations directly from the sun and sky and we avoid looking at the sun. Snow reflects ultraviolet radiation very well, and "snow-blindness" sometimes results from long exposures to bright sunlight on high mountains and in the arctic regions, since the eyebrows and eyelashes cannot protect the eyes under these conditions.

Extensive experiments with the eyes of rabbits, monkeys and human beings with ultraviolet radiation of extreme intensity and duration have shown that the retina cannot be injured by such radiations, since none of them can reach it. The cornea of a normal eye absorbs almost completely all radiations shorter than λ2950. Any of these radiations which may pass through the cornea are completely absorbed by the lens. Using the magnetite arc and concentrating the radiation by quartz lenses after removing a large amount of heat by a watercell, Verhoeff and Bell [11] were unable to injure the lens of a rabbit's eye to a greater depth than 0.02 mm.

Injury to the retina may result from the reception of focused images of very bright light-sources such as the sun or an electric arc, but the injury is due to thermal effects rather than ultraviolet radiation. In the case of electric short-circuits, the cornea may be seriously injured by the large amount of ultraviolet energy of short wavelengths.

Burge [12] found that the most effective region of the spectrum in coagulating the living material of cells or protoplasm lies between λ2490 and λ3020, the greatest effect being observed at about λ2540. He concluded from his experiments that cataract was caused by ultraviolet radiation acting upon the eyes in the presence of excessive amounts of certain alkalies.

In the development of artificial sunlight we have made hundreds of erythemal tests during which the outer membrane of the eyes was exposed to relatively high intensities of illumination (as high as 500 footcandles) with the Sunlight (Type S-1) tungsten-mercury arc. More than 100 footcandles was due to the mercury arc (the remainder being emitted by the incandescent tungsten) and all wavelengths as short as λ2800 were present in abundance. In addition, a relatively slight amount of energy from λ2800 to λ2600 was also present. Deliberate exposures far in excess of those which would be experienced in a general use of artificial sunlight caused no suggestion of conjunctivitis. Reading three hours from a book illuminated to an intensity of 300 footcandles (70 footcandles due to the mercury arc with a glass transmitting freely to λ2800) caused no inflammation of the conjunctiva. Therefore, λ2800 is a safe long-wave limit for an artificial sunlight to be used for general lighting which seldom reaches a value of 50 footcandles.

Cosmic rays is the term applied to radiant energy of extremely short wavelengths or high frequencies of unknown or undefined limits. In fact, limits of arbitrarily-named ranges of the spectrum generally are not well defined so that the terms should be recognized as meaning a locality in the wavelength scale without being definitely fenced. The existence of cosmic rays has been known or suspected for several decades

but Millikan has studied them extensively during recent years. They are the most generally penetrating radiation known—at least compared with the wavelengths shorter than the visible spectrum. Apparently they originate largely, if not entirely, in stellar laboratories. Millikan's work connects them with atom-building processes under the extreme environment in nebulæ and stars which in a sense provide the primordial conditions for such processes to exist. Possibly they are also going on in the earth. The building of atoms of helium, oxygen and silicon out of the simpler atom, hydrogen, accounts for the penetrability of cosmic rays as determined by the absorption coëfficient of water. Regardless of their source this radiant energy is continually flooding living things and their life-processes upon earth. There is not the slightest evidence that these rays have any influence upon life on earth but there is no proof that they have not. In fact, owing to their extreme penetrability it will not be easy to assemble such proof.

Gamma rays (region of λ0.1) exist under natural conditions in small quantity. Through the concentration of relatively large quantities of radium and its breakdown products man has produced them in relatively high intensity. They have proved valuable in the cure of disease, such as abnormal growths, but there is no proof of their essentiality to life-processes. They are produced by radioactive elements. For example, certain descendants of radium emit alpha particles (protons), beta particles (electrons) and gamma rays. The first two are the positive and negative "atoms" of electricity. Gamma rays, apparently, are radiant energy of certain wavelengths.

Cathode rays are neither radiant energy of certain wavelengths nor ordinary material particles. They are electrons, the unit or "atom" of negative electricity emitted by the cathode in a fairly high vacuum. They will pass through thin solids and may prove valuable biologically. They are not found in Nature excepting perhaps at very high altitudes where the atmosphere is sufficiently rarefied. They produce fluorescence, ionization, photographic action, and heat. When they encounter matter they generate Röntgen rays.

Positive rays are not radiant energy of certain wavelengths nor ordinary particles. They consist of positive ion or protons much greater in mass than the particles of cathode rays. They have strong ionizing, fluorescing and photographic action. On striking a surface they generally roughen it and much of their energy of mass in motion is transformed into heat. They move from the anode to the cathode; that is, in a direction opposed to that of cathode rays.

Röntgen rays (λ0.1 to λ5.0) are radiant energy in the sense that they possess wavelengths. They are named for their discoverer. When so-called cathode rays encounter matter they generate what was first termed X-rays because of their unusual properties, including extraordinary penetration of substances. They cannot be deflected by electric and magnetic fields as cathode and positive rays are. They carry no electric charge and are known to possess wavelengths or something equivalent to them. They are produced in an electric discharge tube in which a fairly high vacuum has been produced. Cathode rays are directed toward a target—an anticathode—by having an anode in line with it and beyond it. When they collide with the metallic target Röntgen rays are generated. Besides possessing high penetrability which varies with the density of the substance, they produce fluorescence, photographic action and many other well-known effects. These do not exist in Nature in appreciable intensity. Man-made devices yield them in sufficient abundance to be valuable in the cure of diseases. Apparently, they are destructive to many life-processes. In their longest wavelengths they overlap those of extreme ultraviolet radiation. These two energies are identical when their wavelengths are equal.

Extreme ultraviolet radition (λ2000 and shorter wavelengths) is absorbed by most substances including air. In general, this is the region of wavelengths which are the least

penetrating of all radiant energy. They must be studied in a vacuum with special photographic plates (gelatine being opaque to them) as Schumann did from λ2000 to λ1200 and as Lyman did for energy of wavelengths shorter than λ1200. Radiant energy of wavelengths over most of the range of the extreme ultraviolet is of no importance in Nature because it does not reach the earth's surface from the sun owing to its absorption by the atmosphere. Radiant energy of λ2000 and somewhat shorter passes through a considerable depth of air; however, the transparency of air rapidly diminishes with decreasing wavelength. Some of these radiations are emitted by certain artificial sources, such as the arcs, but they do not travel very far from the source before being absorbed. They are of little consequence biologically excepting for very special studies and for some bactericidal action close to their source.

Middle ultraviolet radiation (λ2000 to λ3000) is an arbitrary subdivision of the ultraviolet region. It is not transmitted by ordinary glass; but special glasses, particularly when free of iron, can be produced to transmit over desired spectral ranges. Excepting for relatively small amounts of energy from λ2900 to λ3000 it is absent from sunlight. This absence is accounted for largely by its absorption by ozone in the atmosphere. Radiant energy of the middle ultraviolet is produced in large quantities by electric arcs and has been used widely in therapy. It is powerfully bactericidal and coagulates albumen (egg-white), the latter effect being greatest at about λ2500.

Being associated with radiant energy of known biological value, its effects are included with the latter in any use of bare electric arcs and quartz mercury arcs. The spectral range shorter than λ2600 is particularly harmful to the eyes, producing conjunctivitis or inflammation of the conjunctiva or outer membrane of the eye. Prolonged exposures to high intensities of energy throughout the entire range of the middle ultraviolet produce conjunctivitis or in the case of sunlight, snowblindness. None of the middle ultraviolet radiation can

enter the eye owing to the absorption of the cornea. Pure water is transparent to the entire range.

Excepting for the longer wavelengths, λ2800 to λ3000, the middle ultraviolet should be excluded or reduced to very low values in artificial sunlight for general use. The maximum effectiveness in the creation of vitamin D by irradiating ergosterol (Plate II), etc., in the production of erythema, and in the cure and prevention of rickets, is near the long-wave end of the middle ultraviolet. Nearly all the known biological value of ultraviolet radiation is due to the spectral range from λ2800 to λ3000. Some claim that there is no antirachitic value in energy longer than λ3020. However, most experimental work has been done with relatively short exposures to sources quite rich in ultraviolet radiation shorter than λ3020. Long exposures indicate the possibility of antirachitic value for energy of longer wavelengths. Threshold values of intensity and of wavelength have not been determined. It is likely that the limiting effective wavelength depends upon the duration of exposure and intensity of radiation.

Near ultraviolet radiation (λ3000 to λ3900) is present in large quantities in solar radiation reaching the earth's surface. Therefore, it must be well represented in a satisfactory artificial sunlight for general use. As in the case of most other effects the limiting wavelength for a given effect depends upon duration of exposure and intensity of radiation. Its lethal effect upon germs has been observed almost throughout its entire range, certainly from λ3000 to λ3650. Its shortest wavelengths very close to λ3000, particularly λ3024 from the mercury arc, possess antirachitic value and produce erythema. Ordinary glass transmits freely down to λ3500 but its absorption diminishes rapidly for shorter wavelengths, usually becoming entirely opaque for energy shorter than λ3100. The actual limit varies considerably with thickness and for different ordinary glasses. Many special glasses have appeared on the market which transmit somewhat further into the ultraviolet than ordinary glasses. However, many of these lose some or all their transparency to the shorter wavelengths under

the action of solar radiation or short-wave ultraviolet radiation from artificial sources.

Apparently, it is the short-wave portion of the near ultraviolet which is responsible for most of the deep pigmentation or tanning of skin. The energy shorter than λ2900, the limit of the solar spectrum, apparently does not penetrate the skin deeply enough to have as much effect upon pigmentation as that between λ2900 and λ3200. For example, the tanning produced by the radiation from a quartz mercury arc is relatively slight as compared with that due to solar radiation for a given degree of erythema produced repeatedly. Other radiant energy having a short-wave limit between that of sunlight and that of the energy from the quartz mercury arc, is likely to rank between these in the permanency of tan produced and in its depth of color. This is quite certain to be true if the spectral distribution of energy is approximately the same. For example, if the short-wave limit of energy from a quartz mercury arc is shortened in successive steps from λ2000 to λ3000, the tanning effect for a given erythema will be greatest for the energy of longest wavelength limit. Besides being a defense against over-exposure tan is of little known value. It is of esthetic importance to some persons. There is some evidence that those who tan best may be benefited most biologically. At least, pigmentation does not close the door to the benefits of ultraviolet radiation.

Pure water is transparent throughout the entire spectral range of near ultraviolet. Most substances which are more or less transparent to short-wave visible radiation have a limit of transparency somewhere in the near ultraviolet, between λ3900 and λ3000.

Visible radiation (λ3900 to λ7600) is that spectral range utilized by the eye for seeing. This photochemical reaction in the retina has fairly definite limits but these vary slightly for different persons. In Fig. 10 it is seen that spectral energy (λ5550) approximately in the middle of the visible spectrum is maximally effective in producing the sensation of luminosity.

The effectiveness diminishes both ways from this wavelength and becomes zero at the two limits. The values when plotted form the spectral visibility curve. It is well that the visibility of radiant energy diminishes rapidly on each side of the maximum. This makes clear vision possible with a simple lens; that is, the eye as a receiving-set becomes satisfactorily selective. Although visible radiation is very important to human beings owing to the highly developed visual organs, we must think and explore beyond this region in order to understand and to utilize the invisible radiant energy which accompanies visible radiation in sunlight and in the energy emitted by artificial sources.

Visible radiation passes through considerable depths of bodily tissue as is readily proved by looking at a light-source with the eyelids closed, by cupping the hand over the lens of a flashlight or by placing a small electric lamp in the mouth. We have tried to see light through the abdomen by placing a powerful lamp near it and viewing the back through an aperture in an opaque screen. The experiments were not successful but it is likely that from a sufficiently powerful source some light would be diffused through this thickest portion of the human body. An ordinary photographic emulsion will record the passage of light through the hand which proves that some short-wave visible radiation passes through it. However, the water and the color of blood limit the transmission of bodily tissue chiefly to the long-wave visible and near infrared. If the lobe of the ear is compressed between two glass plates an ordinary photographic emulsion will be more affected by light passing through the bodily tissue than when the pressure is removed and blood is permitted to flood the lobe.

Bodily tissue consists largely of water which, of course, is transparent to visible radiation. Blood is quite transparent to orange and red rays (λ6300 to λ7600). Therefore, long-wave visible and near infrared radiations penetrate the bodily tissue more than other radiant energy of neighboring wave-

lengths. A source of energy for heating bodily tissue at a depth should emit these penetrative radiations abundantly. Physical considerations indicate that high-temperature sources are best as discussed in a later chapter.

Certainly visible radiation is important in photosynthesis; that is, in the development of chlorophyll and in its function. No similar effect upon the human body is known. In fact, visible radiation is not known to produce chemical action in bodily tissue. In most of the researches in therapy visible radiation has not been isolated; however, it is known that many of the effects of ultraviolet radiation are not produced by visible radiation. Therefore, the known benefits of visible radiation are thermic. In common with infrared they cause hyperemia and sweating by the dilatation of the blood vessels. The reaction occurs as soon as the radiant energy is absorbed and is not delayed as in the reddening due to erythema. This effect stimulates the normal functions and reactions and is considered by many authorities to be a desirable byproduct of therapeutic uses of sunlight and its artificial substitutes.

Short-wave infrared radiation ($\lambda 7600$ to $\lambda 14000$) is more or less defined as of those wavelengths to which water is fairly transparent. Visible radiation will penetrate great depths of water but the transmission-factor of water falls off rapidly from $\lambda 7600$ toward the longer wavelengths. An inch of water is practically opaque to energy of $\lambda 14000$. Between these two wavelengths water is fairly transparent to radiant energy. This is important in the selection of a source of energy for penetrating bodily tissue. We have shown [10] that the most efficient producers of this penetrating energy are high-temperature solids having color-temperatures approaching that of sunlight. The most practicable sources are the high-wattage tungsten-filament lamps. They emit large quantities of radiant energy which penetrate bodily tissue to a depth of several inches.

Long-wave infrared radiation is the region of wavelengths longer than $\lambda 14000$ to the region of electric waves. The solar spectrum practically ends at $\lambda 20000$ although energy of longer

wavelengths exists in small quantities. Water is practically opaque to infrared between $\lambda 14000$ and $\lambda 80000$ (1.4μ and 8μ). Such energy cannot penetrate bodily tissue. It is absorbed on the surface of the body and the heat may be conducted inward by the flesh. Water becomes transparent again to radiant energy between $\lambda 80000$ and $\lambda 500000$ (8μ and 50μ). The temperature of solids which radiate effectively in this region are 360 deg. K and 60 deg. K, respectively. The upper limit is 87 deg. C or about the temperature of a hot-water bag. The lower limit is — 213 deg. C which can scarcely be used to heat the bodily tissue at a depth. This illustrates the folly of non-luminous radiators for heating bodily tissue at a depth as considered from the viewpoint of physics. Certainly a source must pass this physical examination before it can possibly be rated high in heat-therapy.

Electric, Hertzian and wireless waves do not exist in Nature and are of little interest from the present viewpoint. Some interesting experiments are being performed in heating the inner portions of the body with energy of long wavelengths. Apparently they have met with some success but energy of these wavelengths is outside the scope of artificial sunlight. It occupies the long-wave end of the gamut of radiant energy. Like those extremely short wavelengths at the other end of the spectrum (Fig. 8) they are generally penetrative.

TABLE VI

RADIANT POWER IN VARIOUS SPECTRAL RANGES OF SOLAR RADIATION AT THE EARTH'S SURFACE ON A CLEAR DAY

(1 Atmosphere; Sun at Zenith; 8540 Footcandles)

Spectral Range in Angströms	Per Cent of Total Radiation	Milliwatts per sq. cm.
2900—3100	0.022	0.024
2900—3250	0.24	0.26
2900—3500	1.1	1.17
2900—4000	3.9	4.22
4000—7600	43.7	46.8
Short-wave infrared	35.6	38.1
Long-wave infrared	16.8	17.9
Total infrared	52.4	56.0
Total radiation	100.0	107.0

(1.5 Atmosphere; Feb. 15 at Cleveland, O.; 4940 Footcandles)

2900—3100	0.0063	0.0061
2900—3250	0.11	0.11
2900—3500	0.64	0.63
2900—4000	2.8	2.7
4000—7600	42.1	40.4
Short-wave infrared	37.1	35.7
Long-wave infrared	18.0	17.3
Total infrared	55.1	53.0
Total radiation	100.0	96.1

(2.37 Atmosphere; Dec. 21 at Cleveland, O.; 2415 Footcandles)

2900—3100	0.00051	0.00041
2900—3250	0.029	0.023
2900—3500	0.27	0.22
2900—4000	1.62	1.3
4000—7600	39.1	31.4
Short-wave infrared	38.2	30.6
Long-wave infrared	21.1	16.9
Total infrared	59.3	47.5
Total radiation	100.0	80.2

After the survey of various spectral ranges of radiant energy and some of their prominent effects and characteristics it is interesting to look at solar radiation in detail. Table VI is based upon computations by Forsythe and Christison [4] using data of Abbot,[6] Fabry and Buisson [7] and others. Although computed values depend upon the fundamental data used, the procedure is so straightforward that there need be no other source of disagreement. Of course, computed values cannot be used as a measure of biological effectiveness unless the latter is known in relation to wavelengths of energy. However, computations are valuable as guides and as details in a general vista.

We have taken the liberty to include the infrared and to divide it into short-wave and long-wave energy, the dividing wavelength being approximately at λ14000. It will be noted that for a standard atmosphere about 52 per cent of the total solar energy reaching the earth's surface at noon on a clear day in midsummer is infrared radiation. Of this about one-third is in the short-wave region, between λ7600 and λ14000. As the sun declines, daily and seasonally, the amount of total infrared remains fairly constant in the neighborhood of 50

milliwatts per sq. cm. The percentage of total infrared increases from 52 per cent in midsummer to 59 per cent in midwinter. However, the total radiation declines over this period sufficiently to make the total infrared fairly constant.

The influence of the sun's altitude or air-mass upon the quantity of ultraviolet radiation has already been adequately discussed in Chapter III. It should be noted that all values in Table VI are close to maximal values because they are for direct sunlight of perpendicular incidence and for a clear day with average clear atmosphere. Dust, smoke, water-vapor, cloudiness, altitude of the sun, and angle of incidence of solar energy decrease these average maximum values very much.

CHAPTER V

AN ERYTHEMAL BASIS

Measurements are the necessary foundation of any science or art. Progress and understanding are in proportion to the refinement and organization of measurements. Certain instruments, methods, units and quantitative data are "glass-case" standards, suitable only for the laboratory and only of fundamental value. In the production and application of light in the older sense we have many of these laboratory units and measurements; but the footcandle and closely allied quantities are the practicable ones which provide rough gauges of lighting. They are not a measurement of visibility or seeing but they have served well in the absence of simple methods of obtaining an adequate measure of the effectiveness of lighting for vision.

Luminosity is a psychophysiological phenomenon or sensation which is the result of a photochemical reaction in the retinæ of the eyes. The photosensitive substance in the retina responds to radiation over a narrow spectral range, $\lambda 7600$ to $\lambda 3900$, as indicated in Figs. 8 to 10. All illuminants, including sunlight, have invisible radiation of various ranges in wavelength associated with the visible radiation. Still, it is only the visible radiation, appraised for each wavelength as indicated by the spectral visibility of radiation (Fig. 10), which provides light for seeing. It is the amount of this appraisal per watt of electrical energy, in the case of electric light-sources, which determines the luminous efficiency (lumens per watt) of a source of light. Much progress had to be made in measuring instruments and methods and the spectral visibility of radiation had to be determined before a complete foundation was established. Nevertheless, lighting develop-

ment long proceeded apace without these fundamentals. A standard candle was adopted as a unit and light-sources, accurately specified in dimensions, construction and fuel, were developed as portable standards to be used in the laboratory for calibration purposes. A footcandle—the intensity of illumination of a surface perpendicular to the direction of the light-flux and one foot from a standard candle—became a very definite unit long before measurements were sufficiently refined and adequate to provide a complete foundation.

We are confronted with a similar but more complex situation in extending lighting to include health-maintenance as well as vision. Instead of one photochemical process such as vision we have at least several reactions or processes whose spectral sensibilities are not well known. Even these few functions of radiant energy in the rôle of health-maintenance are not well understood and there may be other reactions or processes of which we have no inkling at present. Apparently the most important spectral range is close to the short-wave end of the solar spectrum extending chiefly from $\lambda 2800$ to $\lambda 3100$. Within this range it appears that three important maxima exist—the maximum of production of vitamin D in the irradiation of ergosterol (near $\lambda 2800$) and the maxima of erythemal and antirachitic effectiveness (near $\lambda 2970$). This spectral range (Figs. 10 to 12) of important known biological value immediately becomes as important in dual-purpose lighting as the spectral range of visibility was in the older single-purpose lighting. Energy measurements are of no value in health-maintenance until appraised in terms of biological or physiological value. They will not be of much value unless spectral biological effectiveness is accurately known for the various reactions and processes. Likewise, computations are of little value without such knowledge.

Energy computations and measurements, spectral and for spectral ranges, are at present of some value as approximations or crude compasses. At the present time accurate knowledge of the influence of spectral energy upon biological reactions and processes is meager, but sufficient is known to proceed with

the production and utilization of artificial sunlight. Lighting for vision did not await the entire construction of the foundation. Lighting for health and vision is no more content to await its complete foundation.

Energy measurements have still a further handicap in the new-era lighting. We are now concerned with ultraviolet energy near the limit of solar radiation and, in the case of artificial sunlight, near the limit of transmission of the bulb or glass filter which makes the radiant energy safe for the eyes. As a consequence, measuring instruments are often called upon to determine exceedingly small quantities of spectral energy. This stresses their sensibility usually beyond the limit of dependability or, at least, of satisfactoriness. Energy within a small spectral range is usually of sufficient quantity to be measured accurately; but the isolation of the spectral energy in such a manner that it has biological significance is not accomplished satisfactorily by transmitting filters. Ultraviolet radiation produces a far greater variety of effects, including thermal, chemical, photoelectric, photographic, and fluorescent, than energy of any other spectral range (excepting possibly the Röntgen region). Any of these effects are potential methods of appraisal of ultraviolet energy. These are discussed in later chapters.

While the development of measuring devices and methods and the accumulation of knowledge pertaining to biological effectiveness are progressing we have adopted a parallel method or basis of appraisal—the production of erythema and its relation to footcandle intensities from specific potential sources of artificial sunlight. Even when adequate knowledge and measurements become available the footcandle-erythema basis is likely to be the most practical and important one. Energy measurements will be welcome and helpful but it seems safe to assume that they will provide chiefly laboratory data and glass-case standards. The footcandle should always remain the quantitative measure of intensity of illumination regardless of its limitations as an appraiser of lighting for seeing. In fact, it seems safe to predict that the biological effectiveness

of an illuminant will be standardized eventually in terms of footcandles and the hours of exposure to new-era lighting—and then retire from the spotlight where the footcandle will remain. Now we are accustomed to artificial light for vision and most persons take it for granted. Artificial sunlight for curative and health value is new and unassociated with lighting for vision.

As installations outgrow the portable-unit stage and enter the nursery, gymnasium, play-room, etc., health-value may remain for some time in the consciousness of the adult user. But, eventually, if and when new-era lighting spreads to general lighting in the work-world of offices and factories, the health-value will be relegated to the background of consciousness and light which the eyes use—footcandles—will occupy the consciousness predominantly and perhaps entirely. Then the new-era lighting with simulated sunlight will have challenged the sun completely. Attitude toward it will be the same as that now exhibited toward natural sunlight. We go outdoors deliberately for the health-value of sunlight but, if conscious of the sunlight at all, we accept it as an aid to vision rather than as a benefit to health.

An examination of Fig. 12 and Table IV with other biological data in mind indicates that the spectral erythemal or rubescence values encompass a range of maximum biological importance. Furthermore, the maximum of effectiveness is at a wavelength either coincident or fairly close to that of the antirachitic maximum. Cutting off the radiation shorter than $\lambda 2800$ in order to make a simulated sunlight safe for the eyes we have a narrow range, $\lambda 2800$ to $\lambda 3100$, isolated automatically when the production of a given degree of erythema is taken as a measure of biological effectiveness. Knowledge is inadequate at present so that no guarantee of an exact representation of biological value by means of erythemal effect can be made. But the approximation is sufficiently close for the purpose of lighting with simulated sunlight for which large factors of safety are available in the skin's capacity and

must be allowed in order to cover the wide range of exposure to it.

There is another reason for developing the erythemal basis. Although it is not necessary to expose the skin long enough to ultraviolet energy intense enough to cause erythema even in its slightest degree to obtain adequate benefit, the conditions which produce a certain degree of erythema will be the limiting ones. Whether the limiting conditions will be those which produce a minimum perceptible erythema or a greater degree of rubescence will be determined by experience. It is likely that the former will provide the basis for developing and using simulated sunlight. This would allow a large factor of safety to take care of unusually long exposures and the relatively few abnormally sensitive skins.

Certain fundamental factors and relationships had to be determined in order to establish the satisfactoriness of the erythemal basis as a fundamental for the new-era or dual-purpose lighting. Assuming the short-wave limit of the spectrum of an artificial sunlight to be at $\lambda 2800$, or other wavelength which assures safety to the eyes under reasonable usage, intensities and exposures, it is necessary to limit the ultraviolet radiation so that long exposures under economic levels of illumination do not produce a high degree of erythema. The difference in exposure-time for minimum perceptible erythema and the second, third and fourth (blistering) degrees must be established. Artificial sunlight must compare favorably with midday midsummer sunlight in these and other factors. Finally, the reciprocity law (time of exposure $\times$ intensity of illumination = constant) must hold over a practicable range of hours and footcandles if the erythemal basis is to be satisfactory and an artificial sunlight is to be suitable. All these and associated factors have been adequately studied to lay the foundation for the erythema-footcandle basis and for dual-purpose lighting.

Various potential sources of artificial sunlight are discussed in later chapters, but in order to develop the present discussion certain sources had to be studied comparatively. The results

are used herewith without the necessity of describing the sources in detail. Incidentally, the only source of artificial sunlight which has been developed primarily and solely as an artificial sunlight for dual-purpose lighting is the Sunlight (Type S-1) lamp. It consists of a tungsten filament in parallel with a miniature mercury arc between tungsten electrodes. About 80 per cent of the visible light for vision is emitted by the incandescent tungsten (filament and electrodes) but most of the ultraviolet energy for health-maintenance is emitted by the mercury arc. Most of our fundamental studies have been made with this new source and with midsummer sunlight because the latter was the goal of the former. The results were also correlated with those obtained with mercury and carbon arcs.

To the uninitiated, erythemal measurements may seem to be tedious and uncertain. Of course, the untanned skins of individuals vary over a considerable range but one soon learns to recognize a skin of approximately average sensibility. If untanned skin is used, the abnormalities are considerably reduced. A series of holes one-fourth to one-half inch in diameter is punched in a strip of tape. This can be attached to the untanned skin of the back, chest or abdomen. The source is placed at a measured distance from the skin and footcandles (and energy, if desired) are measured at the skin. As the time passes the holes are successively covered and the result is a series of exposures of various durations. For very accurate work we use a second series of holes adjacent to the first as a check. If the intensity of illumination is varied the procedure is obvious. The degrees of erythema are readily standardized by a worker but are difficult to describe in words. The minimum perceptible erythema is very definite. The fourth degree or blistering stage is obvious but not definite. One may readily standardize for himself such degrees as vivid and painful erythemas but we recommend the minimum perceptible as being the most definite and practicable.

An extensive study of the reciprocity law over a range of 25 to 400 footcandles with the Sunlight (Type S-1) tungsten-

mercury arc indicated that equal products of exposure-time and footcandles hold very well over this range for this illuminant. Other studies indicate that the law can be extended to other sources when the footcandles are increased or reduced by the proper factor—the relative erythemal effectiveness per footcandle. From this work the relationships of exposure-time and intensity of illumination in footcandles for minimum perceptible erythema are established for four representative sources as presented in Table VII.

The quartz mercury arc is rated and was operated at 110 volts and 3.5 amperes. The carbon arc is a twin-arc, rated at 1000 watts and burning 6mm. socalled Sunshine carbons. The Sunlight (Type S-1) lamp is a standard 400-watt tungsten-mercury arc with a bulb transmitting radiant energy fairly well to λ2800. It was used in an oxidized aluminum reflector. The spectra of the quartz mercury arc and of the carbon arc extended to much shorter wavelengths than λ2800. Owing to the difference in erythemal radiation emitted per footcandle, the erythemal effectiveness for these four sources differs considerably as shown in Table VIII. If the quartz mercury arc were equipped with a filter which did not transmit energy shorter than λ2800, its erythemal effectiveness per footcandle would be somewhat reduced. It radiates considerable energy shorter than λ2800 and, notwithstanding the lesser effectiveness of these radiations, considerable erythema is produced by them. The carbon arc can use a variety of carbons impregnated so as to emit various quantities of erythemal rays. Therefore, its erythemal effectiveness can be altered considerably. The Sunshine carbons are only moderately rich in the erythemal rays. These carbons do not radiate as much energy shorter than λ2800 as the quartz mercury arc, so that a filter opaque to these radiations would not reduce its erythemal effectiveness per footcandle as much as it would that of the quartz mercury arc.

Exposure should be taken to mean the product of time and intensity. However, this meaning is not generally used, so we

preface the word with footcandle-minutes, as indicated in Table IX. Here the exposures are in terms of the product of intensity in footcandles and the duration of exposure to the energy. Two degrees of erythema are recorded, one being the standard minimum perceptible. More extensive data are presented in Chapters XII and XIII, and especially in Tables XXXV and XXXVII.

TABLE VII

FOOTCANDLES NECESSARY TO PRODUCE A MINIMUM PERCEPTIBLE ERYTHEMA FOR VARIOUS EXPOSURE-TIMES

	10 Minutes	20 Minutes	60 Minutes	180 Minutes
Sunlight and skylight (at noon in midsummer)	...	9000	3000	1000
Quartz mercury arc	30	15	5	2
Sunlight (Type S-1) lamp (tungsten-mercury arc)	400	200	67	22
Bare carbon arc (6 mm. Sunshine carbons)	550	275	92	30

TABLE VIII

RELATIVE ERYTHEMAL EFFECTIVENESS PER FOOTCANDLE

Sunlight and skylight at noon in midsummer	1
Quartz mercury arc	600
Sunlight (Type S-1) tungsten-mercury arc	45
Bare carbon arc (6 mm. Sunshine carbons)	33

TABLE IX

EXPOSURES REQUIRED FOR TWO DEGREES OF ERYTHEMA ON UNTANNED SKIN (SEE TABLE XXXV)

	FOOTCANDLE-MINUTES EXPOSURE	
	Minimum perceptible erythema	Vivid erythema, producing moderate tan
Sunlight and skylight (at noon in midsummer)	180000	450000
Quartz mercury arc	300	700
Sunlight (Type S-1) lamp (tungsten-mercury arc)	4000	10000
Bare carbon arc (6 mm. Eveready Sunshine carbons)	5500	14000
Carbon arc through 5 mm. Corex filter (8mm. Sunshine carbons)	No erythema at 84,000 footcandle-minutes	

It should be understood that a value of erythemal effectiveness per footcandle remains unchanged only as long as the relation of the erythemal and the visible radiation does not change. For example, such a factor established for a bare source ceases to hold when the source is placed in a reflector which does not reflect the erythemal rays equally as well as the light-rays. In dual-purpose lighting the erythemal effectiveness per footcandle will generally be different for radiant-flux directly from the source than for that reflected from ceilings and walls. This is due to the fact that ordinary paints and other surfaces commonly absorb much of the ultraviolet radiation which is biologically effective. Even white pigments which reflect light with equal or comparable efficacy differ markedly in their reflection of erythemal rays. In practice, this difficulty can be readily surmounted; in fact, it will be considerably reduced automatically. In dual-purpose lighting, fixtures must be designed so that most of the light is reflected or diffused generally downward, without appreciable loss in erythemal effectiveness. Fixtures are readily designed to emit the light entirely downward, that is below their horizontal plane. By using oxidized aluminum, chromium and inexpensive diffusing quartz, efficient lighting units can be designed which are also satisfactory from the viewpoint of eye-comfort. If an upward component is desired, as it generally is, to produce a satisfactory lighting effect this can be produced with ordinary filament lamps.

In designing an installation the footcandles of dual-purpose lighting can be considered separately from the lighting with solely a visual purpose. Of course, some of the erythemal effectiveness may be sacrificed deliberately by supplying the desired upward component by means of artificial sunlight and allowing for the reduction due to the absorption of ultraviolet radiation by the ceiling and walls. The ceiling and walls can be covered with aluminum or chromium, or with special paints developed for the purpose. With certain allowances which can be made readily, the reduction in erythemal effectiveness becomes sufficiently well known so that it comes within the

wide range of aggregate factor of safety which is and must be present in dual-purpose lighting. Simple meters which approximately measure biological effectiveness will be very useful but they are neither essential nor fundamental after the erythema-footcandle relationship is known and properly used.

Although the erythemal effectiveness from a source at a given distance is not of interest in dual-purpose lighting after the footcandle relation or factor has been established, it is important in supplying the original foundation. In Table X the time required to produce two degrees of erythema, respectively, is presented for a distance of 30 inches from the artificial sources of interest. Inasmuch as midsummer sunlight is of fundamental importance the time required to produce these two degrees of "sunburn," respectively, has also been determined for average untanned skin. The minimum perceptible degree is very definite. The other degree is best described as vivid. A moderate tan results from it. Vivid erythema is still far from the blistering stage for average untanned skin. Although this stage is not very definite the time required approaches ten times that required to produce a minimum perceptible erythema. From the viewpoint of dual-purpose lighting the measurement of time alone is of little value. The wattage and character of the source influence the time required for erythemal effects to a very great extent. However, with the additional measurement of footcandles we immediately have adequate information for lighting practice.

In connection with Table X it is of interest that two-hour exposures at 30 inches from a carbon arc through a 5mm. Corex glass (8mm. socalled Sunshine carbons) produced no suggestion of erythema. It is also of interest that we have obtained a definite erythema from long exposures to high intensities of radiation from tungsten-filament lamps with special glass bulbs. Tungsten filaments emit considerable ultraviolet energy and definite antirachitic effectiveness has been demonstrated for special-bulb tungsten-filament lamps. Exposures to high-intensity radiation from tungsten filaments

produce marked hyperemia or thermal reddening. However, this effect disappears in a short time so that erythemal reddening, which is delayed and more persistent, should be revealed if it has been produced. Our exposures were made through a quartz water-cell to eliminate much of the infrared.

TABLE X

MINUTES REQUIRED FOR THE PRODUCTION OF ERYTHEMA AT 30 INCHES FROM THE ARTIFICIAL SOURCES

	Degree of Erythema	
	Minimum Perceptible	Vivid
Sunlight and skylight (at noon in midsummer)	20	50
Quartz mercury arc (3.5 amperes, 110 volts)	7	17
Sunlight (Type S-1) lamp, Corex D bulb (400-watt tungsten-mercury arc)	8.5	21
Bare carbon arc (1000-watt) (Sunshine carbons)	16	40

In considering the production of erythema it should be borne in mind that the human body is a complete system including continual processes of repair. If the intensity of erythemal rays is below that where the rate of destruction exceeds the rate of repair, no visible erythema will result, even for extremely long exposures. Nevertheless, it has been proved that biological benefit can be obtained under this condition of sub-erythemal dosage or exposure. In fact, no fundamental relation between erythema and biological benefit has been discovered. From a practical viewpoint erythema is an accompanying destruction of the superficial layers of the skin coincident with biological benefit due to radiant energy of the same wavelengths.

Eventually it is likely that it will become generally recognized that little or no erythema is necessary in order to profit fully in the building and maintaining of health by means of artificial sunlight for relatively long periods during which it is utilized primarily for seeing. This will extend the factor of safety which is already large. From Tables VII, IX and X it is seen that there is a range of 2.5 to 1 in the time re-

quired to produce vivid and minimum perceptible erythemas for radiation having a constant intensity and spectral character. The relative times required for obtaining a painful "burn" and blistering are less definite. Assuming average untanned skin, the approximate relative exposure-times, for the four degrees of erythema, for an artificial sunlight approximately equivalent to midsummer sunlight in essential factors, are as follows:

Degree 1, Minimum perceptible erythema	1
Degree 2, Vivid, producing moderate tan	2.5
Degree 3, Painful "burn"	5
Degree 4, Blistering	10 (?)

It should be understood that these relative values are only approximate and vary somewhat with the spectral character of the radiant energy. They are modified somewhat by the degree of pigmentation but in general present a fairly satisfactory view of the relation between time of exposure and degree of erythema produced. The range of time between the extreme stages of erythema is somewhat reduced for sources emitting radiant energy throughout the middle ultraviolet region compared with sunlight or artificial sunlight whose spectra end in the region of λ2800 and λ2900. As the skin becomes tanned it increases this range because pigmentation affords protection againts over-exposure without seriously reducing known biological effectiveness.

Medical authorities recognize four stages of erythema. From the viewpoint of therapy the first three stages may be beneficial, depending upon the objective. Even the blistering stage may be curative locally; however, in general it is pathological. The first three vary visually from a faint fleeting redness to a vivid redness which is more lasting. Skin reactions are also divided into three classes—stimulative, regenerative, and destructive erythema. Stimulative erythema is a faint reddening causing the least change in cell protoplasm and considerable engorgement of the blood-capillaries. Therapeutically, it is considered useful in general applications of

ultraviolet radiation over a large part of the body. Regenerative erythema is distinguished by a conspicuous hyperemia and later results in a moderate tan of the skin. It is sometimes desirable in therapy even in general exposures of the body. Destructive erythema causes blistering and considerable damage to the skin. It is rarely valuable.

Therapeutic practice is far different from health-maintenance in the severity of treatment, brevity of exposure, intensity of radiation. Its purposes are largely curative, which in general require more heroic measures. In dual-purpose lighting the exposures are long and the "dosages" must for the most part be sub-erythemal. By designing installations so that, for example, in three hours only the minimum degree of erythema is produced on untanned skin, the second stage is removed six hours and the third and fourth stages are far outside the maximum period spent under artificial lighting, excepting a few cases which can be ignored. The shifting of the period for producing the first stage of erythema can be reduced or increased according to judgment gained from experience. Furthermore, with the long exposures under dual-purpose lighting it appears logical to expect that the physiological repair would have an advantage. In other words, a given biological benefit should be obtained with less destructiveness for long periods of exposure than for short ones. If this is true, as appears likely, the factor of safety is further increased.

Unfortunately, ultraviolet therapy has been generally investigated and practiced with high-powered sources of erythemal rays which save time by reducing exposures to the order of a few minutes. We must not apply conclusions gained in the upper scale of dosage to the lower end of the scale or even sub-erythemal dosage as represented by the necessary conditions of dual-purpose lighting. However, we can be guided by that experience modified by new data and combined with intelligence and logic. The region of minimum erythemal dosage needs investigation in order to complete the scanty picture we now have. However, the available factors

of safety seem to be adequate for the development of lighting with extended purpose.

The erythemal basis is also a sound and helpful one for the final appraisal of glass filters and reflecting media. Ultraviolet spectograms are valuable in preliminary work and for reconnaissance. Energy-measuring instruments are useful and various photoelectric cells can be pressed into service. However, dependable spectral energy measurements are not easy to obtain in the ultraviolet region of biological effectiveness. The spectral sensitivity of a photoelectric cell must be known for dependable absolute measurements. However, without this it is useful for determining relative values for energy of constant spectral character. Filters are indefinite as to wavelength limits. Even if all these difficulties are overcome we still have the indefiniteness of spectral biological beneficence. Therefore, the erythemal basis provides a direct appraisal of an important factor for itself and in its intimate spectral association with the known biological beneficial effects. We have used this basis with much success and convenience in appraising energy measurements, proposed methods, materials and other accessories in the development of artificial sunlight and in the construction of the foundation for its use in professional therapy, for home-treatment and in dual-purpose lighting.

Before simulated sunlight can come into general use there must be a period of development of sources, fixtures, and practices. During this period many experiences will arise which could not be anticipated. Along with this development, progress in measuring instruments and in biological research will inevitably be made, owing to the birth of new problems, viewpoints and vistas. Practice should not get too far ahead of fundamental knowledge but experiences and demands in practice always inspire fundamental researches and developments. Neither theory nor practice goes far alone.

CHAPTER VI

Reflection of Ultraviolet Radiation

With the development of artificial sunlight, reflecting media must perform the dual purpose of efficiently reflecting biologically-active ultraviolet radiation as well as light. Many data are available pertaining to the reflectances or reflection-factors of materials for light or visible radiation. Spectral reflection-factors have also been determined for a large number of colored media. As a consequence, adequate data have been available pertaining to the reflection of light and these have been taken advantage of in the development of lighting equipment whose function is to control visible radiation efficiently and satisfactorily.

The eyes can fairly well appraise the efficacy of materials in reflecting light. As a consequence of the habit of appraising the reflectances of materials visually and for light, the mistake has often been made of taking for granted that high reflectance in the visible qualifies a material as a reflector of ultraviolet energy. For example, porcelain enamel is an excellent reflecting surface for lighting equipment designed solely to control light for vision. As a consequence its use has been extended, apparently without investigation, to equipment whose primary function is to control biologically-effective rays for prevention and curative purposes. As a matter of fact, porcelain enamel as made at the present time reflects practically none of the so-called vital energy known to be valuable, for example, in rickets and in the irradiation of ergosterol. A dull black paint reflects better in this ultraviolet region than porcelain enamel or zinc oxide. A silvered glass reflects lights very well but is relatively worthless as a reflector of biologically-active radiation owing to the absorption of the layer of glass.

The dual purpose of reflecting media, to be used in lighting for health-maintenance as well as for seeing, greatly reduces the number of materials which can qualify. High reflectance throughout the range from λ2800 to λ7600 is relatively rare. Of course, as far as is now known, a medium to be satisfactory need only reflect efficiently in the two ranges λ2800 to λ3200 and λ3900 to λ7600; but such selectivity is even rarer and fortunately unnecessary.

Although reflecting media are primarily of interest for their efficacy in reflecting ultraviolet and visible radiation, they may be employed to great advantage in absorbing undesirable ultraviolet radiation. Such applications have not been made but they are bound to be. For example, a quartz mercury arc could be confined between two reflectors whose surfaces absorb practically all the radiation shorter than λ2800. The upper reflector could be the "ceiling" in a sense and a smaller inverted reflector containing the arc could be designed so that its optical cutoff would be within the outer edge of the upper reflector. Thus, a not uncommon design of lighting fixture could become a dual-purpose lighting fixture. By taking advantage of the absorption of energy shorter than λ2800 and a high reflection for energy longer than this wavelength the need for filtering the radiation through a special glass with a short-wave cutoff at λ2800 would be obviated. Such an expedient may be more practicable in some cases than a transmission filter. Of course, there would be some non-selective surface reflection but with a mat surface perhaps this could be minimized to an extent to be harmless for the levels of illumination employed in lighting.

The same expedient has possibilities in devising apparatus for measuring ultraviolet radiation within certain approximate spectral limits. For example, if one is interested in the ultraviolet radiation of wavelengths longer than λ2800, the energy could be admitted to a sphere coated on its inner surface with a medium which absorbed all or most of the radiant energy shorter than λ2800. The effect of the selective reflection or absorption is increased by multiple reflections in a sphere, or

between two plane surfaces which are parallel or form a wedge. Many special uses of reflecting media with suitable selectivity in absorption and reflection can be made.

With the growing interest in the production and use of artificial sunlight knowledge pertaining to the spectral reflection and transmission characteristics of materials increases. Through years of study of ultraviolet radiation we have made such determinations[15] of many reflecting and transmitting media. Data pertaining to materials of interest are presented herewith and augmented[2] by the work of others. Most of the media considered here are those which have or might have

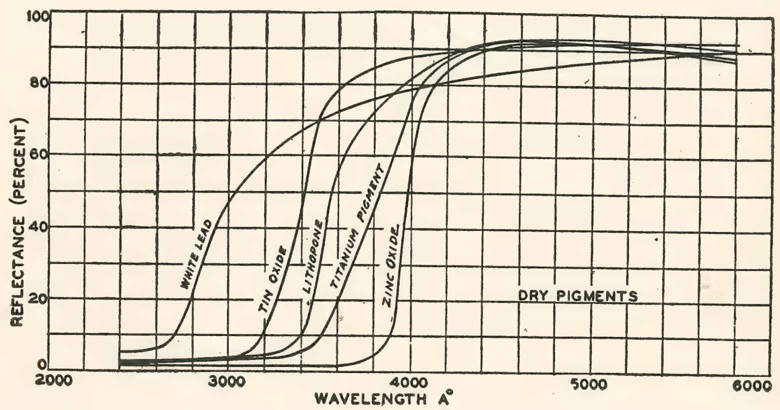

FIG. 13. Spectral reflection of dry pigments.

applications in artificial sunlighting. Others are of interest either for comparison or for special purposes. Pfund,[16] Stutz,[17] and Hurlburt[18] are prominent among those who have contributed valuable measurements of the spectral reflectances of materials. In general, the reflectances of practically all materials which have a high reflectance for visible radiation are less in the ultraviolet region. The reflectances of relatively few substances remain high for energy shorter than λ3200.

Five important dry white pigments having very high and almost identical reflectances for light are seen in Fig. 13 to differ markedly in their reflection of the so-called vital rays

between λ2800 and λ3200. This will be found true in all the illustrations from Figs. 13 to 23. We have found that specimens of a pigment obtained from different sources sometimes differ markedly in spectral reflection characteristic. Whether or not this accounts for the difference between our results for zinc oxide and those obtained by Stutz[17] (Figs. 14 and 15) cannot be stated definitely. At least it is obvious that zinc oxide, although an excellent reflector of light, absorbs almost completely the radiation of known biological value. In fact, white lead is the only promising white pig-

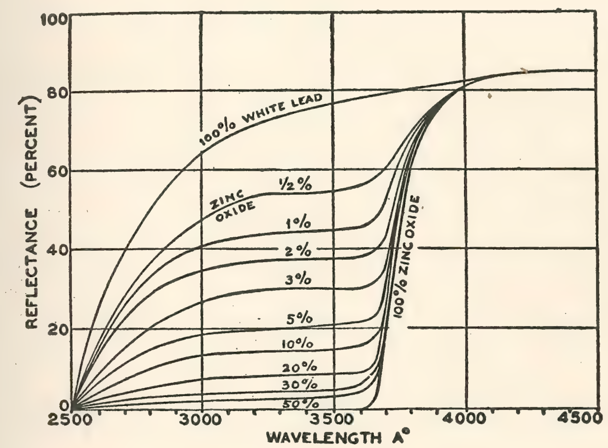

FIG. 14. Spectral reflection of mixtures of zinc oxide and basic carbonate white lead (Stutz).

ment of this group for use in the conservation of radiation between λ2800 and λ3200. The difference in the reflection of ultraviolet radiation of zinc oxide and some of the other white pigments is so marked that it can readily be detected by photographing the pigments with an ordinary silver emulsion and a camera having the usual glass optical system.

Among the common white pigments basic carbonate white lead is one of the best for reflecting ultraviolet radiation. If absorption is desired, such as in the case of employing selective reflection for filtering out certain radiations, these dry white pigments offer an attractive variety. Of course, their

use as paints involves vehicles, such as linseed oil, whose influence upon the spectral reflection of paint must be taken into account. Unfortunately, common vehicles are not very satisfactory in conserving ultraviolet radiation but they can be used sparingly—just enough to bind a proper pigment. Linseed oil and nitrocellulose lacquers used to hold, for example, white lead or powdered aluminum can be used with fair success.

The results of mixtures of pigments are illustrated in Figs. 14 and 15 from the work of Stutz who has studied spectral

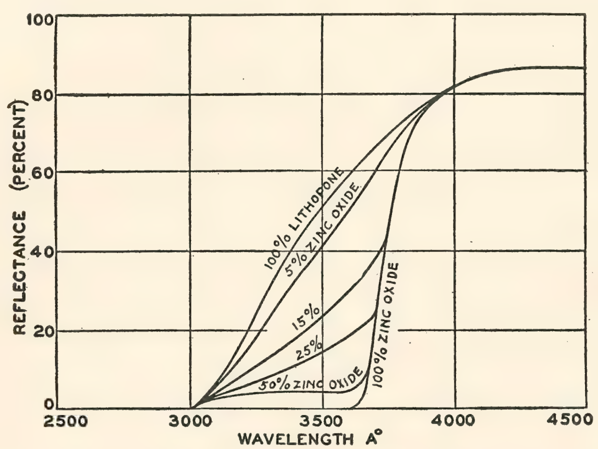

FIG. 15. Spectral reflection of mixtures of zinc oxide and lithopone (Stutz).

reflection of pigments and their mixtures and also the transmission of very thin layers. The results of mixing various portions of two pigments, one a fair reflector of energy between λ2800 and λ3200, are interesting.

Magnesium oxide has a very high reflection-factor throughout the visible and the ultraviolet from λ2500 to λ7600. It is readily obtained by burning a ribbon of magnesium and it may be deposited upon any surface by the simple process of holding the surface above the flame. For spheres and other accessories in experimental work magnesium oxide is useful. Whiting, asbestine, barytes, china clay, precipitated chalk and

terra alba are white pigments of high reflection-factors throughout the range from λ2500 and λ7600.

Data pertaining to common materials in powdered form are presented in Fig. 16. Aluminum oxide is an excellent reflector for so-called vital rays and magnesium carbonate is quite satisfactory. Common plaster reflects practically 50 per cent of the radiation between λ2800 and λ3200. This is of interest in connection with interiors. Powdered silica and opal glass are fairly efficient in the spectral region of interest. Graphite has a low uniform spectral reflectance. The black pigments or powders diffusely reflect from 5 to 10 per cent

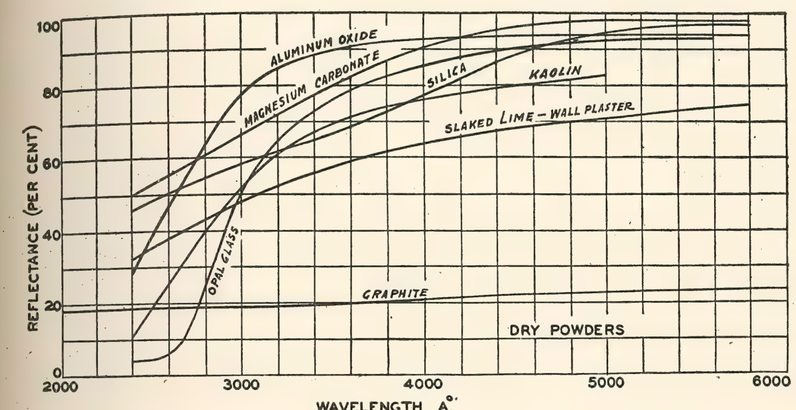

FIG. 16. Spectral reflection of dry powders.

of the incident radiation. There is also a specular reflection which usually accounts for differences in results reported by different investigators. It varies with the dullness of the surface or with the pressure which has been exerted in smoothing a layer of the dry pigment. The addition of powdered aluminum to plaster may be practicable for interior finishes.

In Table XI data obtained by Stutz in extensive investigations of the spectral reflection of pigments are presented with some of Pfund's data included. The reflection-factors are given for energy of wavelengths corresponding to the mercury lines from λ2536 in the ultraviolet to λ5461 in the middle of the visible spectrum (green). The spectral range of bio-

logical interest in connection with artificial sunlight for general use is between λ2800 and λ3200 with chief interest at λ3024 and λ2968. Therefore, the data in the columns headed by the latter two wavelengths are particularly interesting.

Relatively few colored materials reflect as much as ten per cent of the ultraviolet energy of primary interest. Most of them reflect less than five per cent in this spectral region. Some of the data obtained by Stutz are presented in Table

TABLE XI

DIFFUSE REFLECTION-FACTORS OR REFLECTANCES (IN PER CENT) OF WHITE PIGMENTS FOR ULTRAVIOLET RADIATION OF WAVELENGTHS CORRESPONDING TO THOSE IN THE MERCURY SPECTRUM (STUTZ)

Pigment	Per Cent of Energy Reflected							
	5461	4358	4047	3655	3131	3024	2968	2536
Antimony oxide pigment*	97	87	80	69	43	40	36	0
Asbestine	95	84	75	68	63	62	64	55
Barytes	93	85	75	65	66	60	60	54
Basic carbonate (white lead)	95	85	83	78	69	65	62	4
China clay	93	86	76	64	62	60	59	55
Gloss white ($BaSO_4 + Al(OH)_3$)	90	83	75	72	72	71	69	60
Lithopone*	96	92	83	66	2	0	0	0
Extra-strength lithopone	96	92	83	52	2	0	0	0
Magnesium oxide*	98	98	98	98	98	98	98	98
Precipitated chalk	92	89	80	79	81	83	83	88
Silex	93	81	76	70	60	59	58	55
Sublimed white lead	96	85	82	60	58	57	56	5
Terra alba	91	90	86	86	86	85	88	90
Titanium pigment*	97	86	82	24	2	0	0	0
Whiting	93	85	77	74	65	65	60	56
Zinc oxide*	97	87	80	3	0	0	0	0
Zinc oxide (35% leaded)*	95	82	75	3	0	0	0	0
Zinc sulphide	97	86	75	37	1	0	0	0

* From data of Pfund.

XII. We have taken the liberty of altering his values to the nearest whole number. These data are included more to emphasize the fact of general absorption of ultraviolet energy by colored media. This is true of vegetation, earth, wall coverings, furnishings and practically all the colored objects encountered. Rarely is there an exception. We have studied hundreds of dyes and pigments with the hope of finding exceptions because selectivity in reflection and in transmission

is often an excellent tool in the laboratory. Relatively few appreciably reflect or transmit biologically-active radiation. Table XI may be useful in selecting a pigment for the special purpose of absorbing ultraviolet energy. We have had occasion to make recommendations for painting the surroundings where arc-welding is done and for similar purposes.

TABLE XII

DIFFUSE REFLECTION-FACTORS OR REFLECTANCES (IN PER CENT) OF COLORED PIGMENTS FOR ULTRAVIOLET RADIATION OF WAVELENGTHS CORRESPONDING TO THOSE IN THE MERCURY SPECTRUM (STUTZ)

Name of Pigment	Per Cent of Energy Reflected								
	5461	4358	4047	3655	3131	3023	2968	2652	2536
Blue lead, sublimed	20	23	24	17	11	10	9	4	3
Cobalt blue	22	49	31	12	9	6	6	..	2
Prussian blue	1	3	4	4	3	2	..	..	2
Turquoise blue	32	50	41	35	25	25	23	22	22
Ultra blue	8	47	45	40	23	13	10	..	5
Bone black	2	2	2	2	1	1	1	..	1
Carbon black	5	5	5	5	5	5	5	..	2
Cadmium lithopone	75	6	6	4	4	4	4	4	4
Chrome green	9	5	4	4	3	2	2	2	2
Chrome yellow	60	4	4	3	0	0	0	0	0
Iron oxide 97%	6	5	6	6	6	5	6	6	6
Lampblack	5	5	4	4	4	4	5	5	4
Madder lake	4	7	10	11	5	5	..	1	1
Mercuric sulphide	6	6	6	6	6	6	6	6	6
Ochre, American	48	19	11	7	4	3	3	..	2
Ochre, French	50	14	10	9	8	7	5	..	5
Orange mineral	8	7	6	5	5	5	..	..	5
Red lead	8	6	6	7	8	7	7	7	8
Scarlet lead chromate	7	5	4	4	3	3	3	3	3
Sienna, burnt Italian	6	4	4	4	3	3	3	..	0
Sienna, American raw	21	7	5	4	3	3	..	..	1
Tuscan red	9	10	10	6	6	5	4	..	4
Zinc dust (blue powder)	19	20	21	4	5	5	4	4	4

Results for a few paints are presented in Fig. 17. Aluminum paint consisting of lacquer and powdered aluminum reflects from 40 to 50 per cent of the energy between λ2800 and λ3200. This is low for a paint as appraised by experiences in, and demands of, lighting-practice; but considering that most substances are relatively inefficient reflectors of ultraviolet energy, we may be obliged to lower our standard where paints and other reflecting media are necessary in dual-pur-

pose lighting. Furthermore, considerations of esthetics and eye-comfort demand that walls be of moderate reflectance or

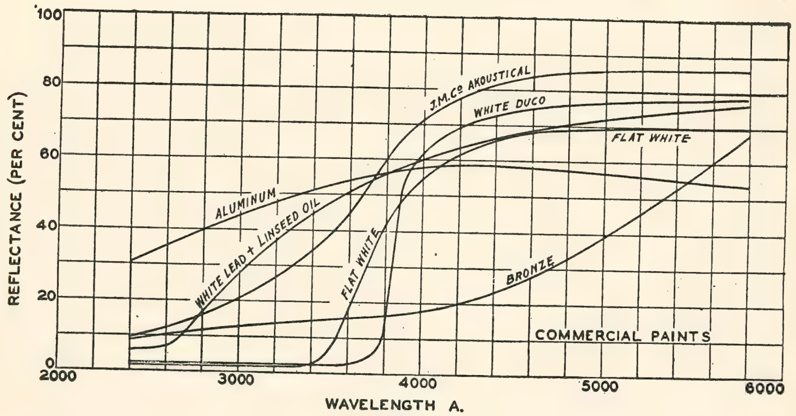

FIG. 17. Spectral reflection of commercial paints.

reflection-factor. As a consequence, paints and other wall finishes which do not efficiently reflect light are acceptable in

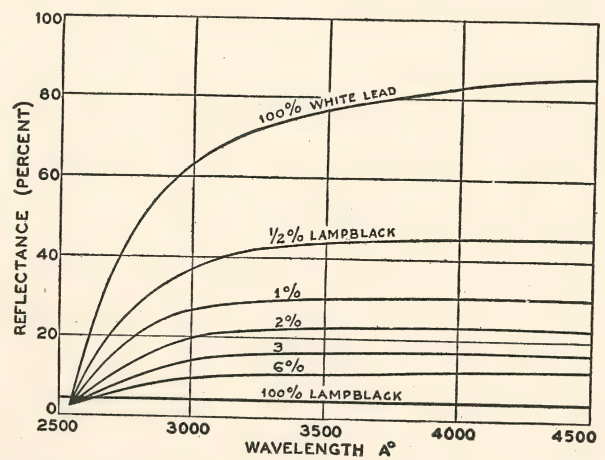

FIG. 18. Spectral reflection of grays produced by mixtures of lampblack with basic carbonate white lead (Stutz).

lighting although not for lighting equipment. Of course, this argument does not directly apply to invisible ultraviolet energy but it tempers our demands somewhat.

In Fig. 17 it is seen that a paint consisting of white lead and linseed oil reflects less than 50 per cent of the energy between λ2800 and λ3200. It is interesting to speculate upon the pigments used in the flat-white and the white Duco lacquer. Although the two vehicles used absorb much of the ultraviolet energy of interest, it is likely that the pigments limit the short-wave cutoff more than the vehicles.

The results of mixtures of lampblack with basic carbonate white lead in producing a series of grays from "black" to "white," are presented in Fig. 18. This combination is among the best obtainable with common pigments, for producing grays for reflecting energy between λ2800 and λ3200.

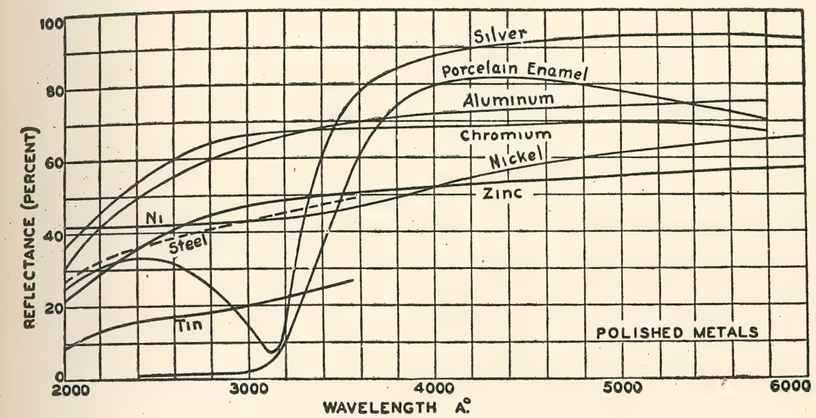

FIG. 19. Spectral reflection of polished metals.

In Fig. 19 it is seen that porcelain enamel reflects practically no energy shorter than λ3200. As at present used for lighting equipment it must be radically modified if it is to serve for equipment to control artificial sunlight. That it now absorbs the so-called vital rays is not surprising. The "vehicle" is, in a sense, a common glass. This alone can account for its absorption in the important region of the ultraviolet spectrum. But white pigments are also used in porcelain enamel. These, as has been seen, vary greatly in their spectral reflectance in the ultraviolet region of particular interest. However, until porcelain enamel is altered in respect to the vehicle, nothing

can be gained through the selection of a satisfactory pigment.

Silver has a unique spectral reflection characteristic. It possesses an absorption band, a rare exhibition for solids, in the vital spectral region. Chromium and aluminum are good reflectors in the visible and in the ultraviolet region. This is fortunate because they supply an urgent need in lighting equipment for producing and conserving ultraviolet radiation. Aluminum oxide is even a better reflector throughout the spectral region of importance. Fortunately, aluminum is oxidized very simply and cheaply by standardized processes in which the metal is immersed in a solution of chemicals. Therefore,

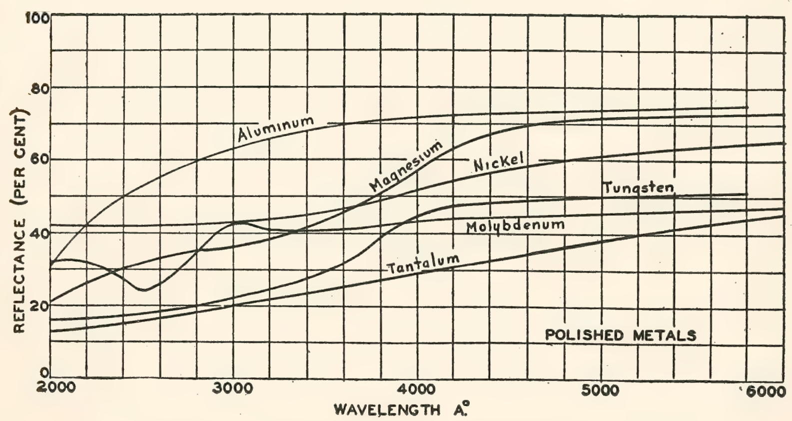

FIG. 20. Spectral reflection of polished metals.

equipment with reflecting surfaces of oxidized aluminum is already in use in controlling artificial sunlight.

Polished nickel, zinc, cobalt and steel, reflect between 40 and 50 per cent of the energy between $\lambda 2800$ and $\lambda 3200$. In this spectral range the reflectance of gold is about 35 per cent; bismuth, selenium, copper, and brass, about 25 per cent. In Fig. 20 the spectral reflections of some of the less common metals are presented and data pertaining to some of the alloys are plotted in Fig. 21. In some of these curves use has been made of Hurlburt's data to average with, or to extend ours.

The spectral reflection-factors or reflectances of some common fabrics are presented in Fig. 22. Some of these were

determined years ago in connection with questions pertaining to protection from short-wave solar radiation in the tropics. Certainly there is too much of this energy in the region of low

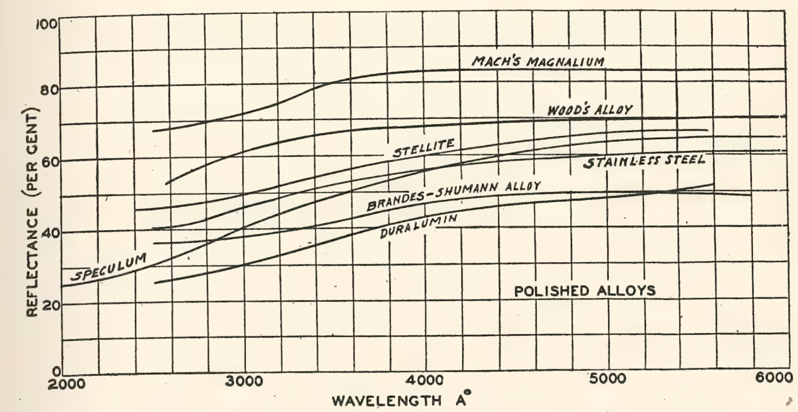

FIG. 21. Spectral reflection of polished alloys (Hurlburt).

latitudes and intense sunlight. Fortunately, bleached cotton, inexpensive and in general use, reflects ultraviolet radiation most efficiently. Linen ranks next and bleached wool and

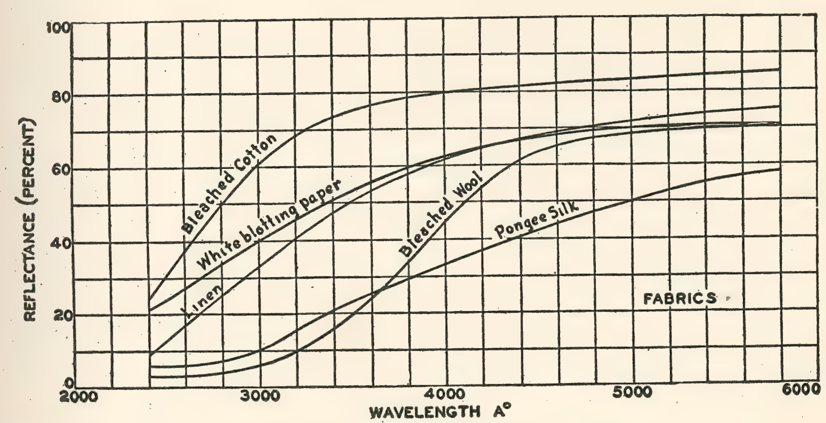

FIG. 22. Spectral reflection of common fabrics.

pongee silk are very inefficient reflectors. Of course, low reflectance does not necessarily mean high transmission. However, high reflection is a safe quality for tropical clothing.

Transmission involves not only the transparency of the fibers or threads but also the mesh or looseness of weave. Interesting uses can be made of the high reflectance of bleached cotton in the control of artificial sunlight. White blotting paper and other white papers are fairly efficient in reflecting ultraviolet

TABLE XIII

MATERIALS ARRANGED IN FIVE CLASSES ACCORDING TO THEIR AVERAGE REFLECTION-FACTOR IN THE SPECTRAL RANGE FROM λ2800 TO λ3200

(METALS ARE POLISHED AND PIGMENTS ARE DRY POWDERS UNLESS OTHERWISE STATED)

	(Reflecting 60 per cent or more)	
Aluminum, oxidized	Cotton, bleached	Snow
Aluminum	Magnalium	Terra alba
Chalk, precipitated	Magnesium carbonate	Whiting
Chromium	Magnesium oxide	Wood's alloy
	Silex	
	(Reflecting 40 to 60 per cent)	
Aluminum paint	Nickel	Speculum
Asbestine	Paper, white	Steel
Barytes	Plaster	Steel, stainless
China clay	Platinum	Stellite
Cobalt	Schröder's alloy	White lead
Kaolin	Silica, powdered	White lead, sublimed
Lime, slaked	Silicon	Zinc
	(Reflecting 20 to 40 per cent)	
Antimony	Iron	Ross' alloy
Antimony oxide	Lead	Selenium
Bismuth	Linen	Speculum
Brashear alloy	Magnesium	Tantalum
Cadmium	Molybdenum	Tellurium
Copper	Opal glass, powdered	Tin
Duralium	Palladium	Tungsten
Gold	Rhodium	White lead in linseed oil
	(Reflecting 10 to 20 per cent)	
Bronze paint	Graphite, hard	Silver
Carborundum	Silk, pongee	Tin, tarnished
	(Reflecting less than 10 per cent)	
Bone black	Iron oxide	Titanium pigment
Carbon black	Lithopone	Wool, bleached
Cyanine	Porcelain enamel	Zinc oxide
Flint glass surface	Tin oxide	Zinc sulphide

radiation. In lighting-practice with artificial sunlight this may be found desirable for reflecting the energy to the face of the person working or reading by means of artificial sunlight overhead or to one side. On the other hand a more extended use of yellow paper for absorbing ultraviolet energy might arise. These are details that experience will determine but the physical data are necessary to guide the judgment.

For convenience, a summary is presented in Table XIII in which reflecting media have been classified into five groups according to their efficiency in reflecting ultraviolet radiation between λ2800 and λ3200. Those reflecting 60 per cent or more of this energy may be considered very efficient. In fact, considering the generally lower reflection-factors in the ultraviolet region those materials which reflect between 40 and 60 per cent may be considered quite efficient. Owing to the difficulty of describing many substances and to the variation of specimens the rank of some of the substances may differ somewhat, depending upon the purity and character of surface of the specimen. Unless otherwise stated, the data pertain to pigments in a dry powdered state and to metals with clean polished surfaces.

Many other substances remain to be studied but it is seen that enough common metals and pigments possess high reflection-factors in the ultraviolet region of particular interest to provide materials for reflecting equipment and pigments for paints and enamels. Common vehicles for pigments do not conserve ultraviolet energy very well but if linseed oil and commercial lacquers are used sparingly certain paints can be made to serve fairly well. If they are sprayed or otherwise applied with just enough vehicle to bind the pigment they will reflect moderately well in the spectral region of interest. Several pigments are available for use with water. After such "water whites" dry they are very efficient reflectors of ultraviolet radiation but of course are not durable. Artificial sunlighting will stimulate research in this field and doubtless excellent paints will be developed. However, the materials for

very efficient fixtures for dual-purpose lighting are available. Polished or dull chromium and particularly polished or oxidized aluminum are almost as satisfactory as could be desired. Other developments will be interesting and useful and doubtless will follow closely upon the creation of demand for them. In this connection the work of Stutz [17] on the transparency of very thin layers of pigments is of interest.

Recently Coblentz and Stair [41] published data pertaining to the spectral reflection-factors of aluminum, duralium, rhodium, and tin. Their results for aluminum are lower than those obtained by us. In the region of $\lambda 2800$ to $\lambda 3200$ polished cast aluminum reflected between 40 and 50 per cent; rolled aluminum sheets, between 20 and 30 per cent; rhodium and duralium, between 30 and 40 per cent; freshly polished tin, between 35 and 40 per cent; slightly tarnished tin between 20 and 30 per cent.

CHAPTER VII

Transmitting Media

As has been seen in the preceding chapter relatively few materials reflect ultraviolet radiation efficiently in the spectral region of primary importance. This is equally true of the transmission of substances. Considering the entire gamut of wavelengths of radiation artificially produced or of natural origin, the known biologically-effective radiant energy lies in a spectral range near the region of greatest general absorption by materials (Fig. 8). The ultraviolet radiation of extremely short wavelengths is absorbed by most substances including air. From $\lambda 1850$ down to $\lambda 200$ ultraviolet radiation must be studied in a vacuum with reflecting diffraction gratings or fluorite prisms. Fluorite is transparent to ultraviolet radiation as short as $\lambda 1250$ but specimens vary so much in transparency to the short wavelengths that it is difficult to find suitable specimens of large size. Ordinary thicknesses of air transmit fairly well the radiant energy longer than $\lambda 1850$ but depths approximating one atmosphere are opaque to radiant energy shorter than $\lambda 2900$. Even pure air of greater depths (air-mass greater than unity) increases in opacity near the short-wave cutoff so that the short-wave limit of solar radiation recedes toward longer wavelengths as the mass of pure air increases.

Owing to the general increase in absorption from the long-wave ultraviolet to the short-wave region it is not surprising that we find few substances transparent to the biologically-active rays. It is not even surprising to find ordinary glass, developed for its transparency to light, to be opaque to the ultraviolet radiation of primary interest in natural and artificial sunlight. However, scientific research has improved over Nature in so many ways that satisfactory transmitting materials

will likely be developed for any purpose. Even in the past decade much progress has been made owing to the increasing interest in ultraviolet radiation.

Among natural substances quartz crystals are the most transparent to ultraviolet radiation as short as λ2000. Optical parts are made of these crystals and of fused quartz made of crushed crystals. Even fused silica is very transparent throughout the middle and near ultraviolet. This transparency is of great advantage in the production and study of short-wave ultraviolet, but the spectral range of transmission must be reduced to about λ2800 in order to make sources rich in short-wave radiation safe for general use in dual-purpose lighting.

At the other extreme are the common clear colorless glasses with short-wave cutoffs varying from λ3100 to longer wavelengths. These do not transmit the biologically-active rays which are generally shorter in wavelength. Of the commonly available materials we are confronted with extending the transparency of glass as far as λ2800 at least or of reducing the transparency of quartz to this wavelength limit. Of course, quartz can still be used in the production of artificial sunlight in connection with a glass filter which safely limits the short-wave radiation. Diffusing quartz is destined to play an important part in lighting fixtures for the new era of artificial sunlighting and perhaps it may be worth while to attempt to limit its spectral transmission to the region of λ2800.

Although ultraviolet radiation was discovered in 1801 its bactericidal action was not discovered until 1877 when Downes and Blunt proved its sterilizing power. In 1892 Ward published results of the exposure of cultures to radiant energy from the sun and from the carbon arc. He found that a thin sheet of ordinary glass interposed between the source and the culture eliminated the potency of the energy as a germicide. Finsen was already at work and the general interest in sunlight-therapy inspired much research. By 1904 it was definitely established that ordinary glass robbed solar radiation of much of its value. Naturally the increasing importance of ultraviolet radiation not transmitted by ordinary glass led to experimental work along this line.

Schott at Jena was perhaps the first manufacturer to catalogue a commercial glass which transmitted the biologically-active radiation to some practicable degree. Anyone interested in glass for the past two decades has witnessed marked advances and developments of glass technology in Germany. In fact, it has been possible to recognize many glasses springing up elsewhere as those born years before in that country. The first glass of this character which emanated from Jena was known as Uviol. It was the result of the work of Zschimmer,[19] reported first in 1903.

In 1907, Fritsch [20] reported that a pulverzied mixture of 6 parts (by weight) of calcium fluoride (CaF_2) with 14 parts of boric oxide (B_2O_3) when fused produced a glass very transparent to ultraviolet radiation. Boric oxide transmits ultraviolet radiation very efficiently but not as well as quartz. It should be noted that many glasses can be made quite transparent throughout the biologically-active region of the spectrum but they may not be satisfactory from other viewpoints such as ease of melting and fabricating, strength and durability. A glass to be used in windows must resist weathering fairly well. The transmission of the desirable ultraviolet energy in sunlight was the primary objective of these early researches. For use in the production and utilization of artificial sunlight, glasses need not be very resistant to weather conditions.

Crookes [21] published considerable data in 1914 showing the effect of adding various metallic oxides to the constituents of glass upon the cutoff in the ultraviolet as well as in the infrared regions. In 1918 we reported the increase in transmission near λ3000 due to the addition of a slight amount of cobalt oxide to an otherwise clear glass. This observation had been made some years before during the development of certain glasses with the co-operation of W. M. Clark and D. A. Dewey. In 1919 Wood,[22] in collaboration with Gage

and Taylor, produced a glass containing nickel oxide which transmits ultraviolet radiation but no appreciable visible radiation. Lamplough in 1924 produced Vitaglass and is deserving of much credit in meeting a demand fairly satisfactorily.

The spectral transmission of glass is limited both by the

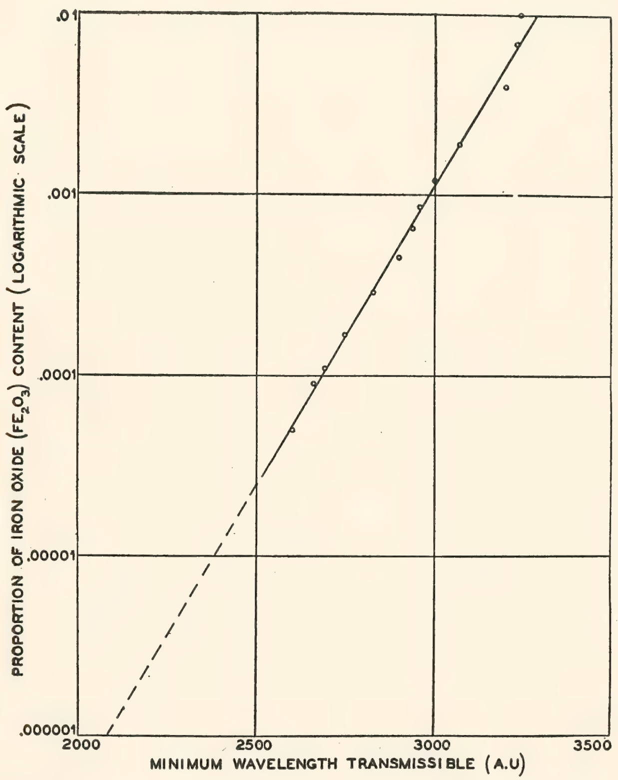

FIG. 23. Illustrating the influence of minute quantities of iron oxide upon the shortest wavelength of energy transmitted by a glass 2 mm. thick and having an approximate composition of 75 SiO_2 + 15 Na_2O + CaO.

ingredients of the formula and by impurities. Assuming that the former are properly selected the most annoying impurity is iron. It is present in some of the raw materials, such as silica, and it also finds its way into the molten batch from the tools, crucibles, ambient gases, and other sources. Even with iron-free raw materials it is very difficult to keep iron out of

glass and unfortunately it has a powerful influence upon the short-wave cutoff of clear glasses.

Tsukamoto [23] found that the limit of transparency of colored quartz varied considerably with the nature of its impurities. A specimen of green quartz was transparent to λ1860 and the short-wave limit of transparency of a yellow specimen was λ2600. Starkie and Turner [24] investigated the limiting wavelengths of radiation that traversed eight commercial soda-lime-silica bottle glasses colored with oxides of iron. The

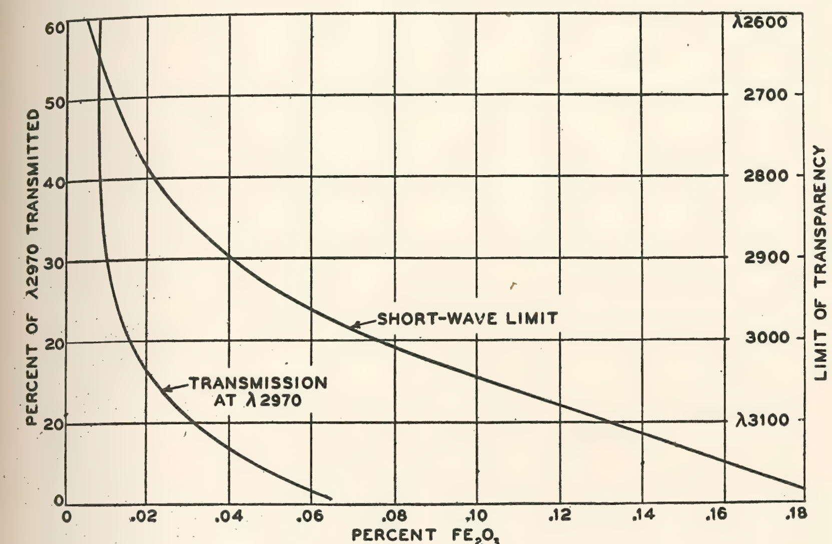

FIG. 24. The influence of iron oxide upon the transparency of glass to energy of λ2970 and upon the short-wave cutoff.

glass containing 0.05 per cent Fe_2O_3 had a short-wave limit of transparency at λ2960. Four other glasses containing 0.07 per cent Fe_2O_3 transmitted only as far as λ2995. A pale green glass with 0.18 Fe_2O_3 had a short-wave limit at λ3175.

Starkie and Turner [25] made melts of a series of soda-lime-silica glasses having the approximate composition 75SiO_2, 15Na_2O, 10CaO and a small amount of iron oxide. By plotting their results on a logarithmic scale for amount of iron oxide and the shortest wavelength of radiation trans-

mitted by a given thickness, a straight line is obtained as in Fig. 23. It is interesting to note the influence of minute quantities of Fe_2O_3. Perhaps it is safe to extrapolate somewhat. If this impurity could be reduced to one part in a million the transparency of a glass of suitable ingredients might be extended nearly to λ2000.

The influence of iron oxide is also shown in Fig. 24. Here the data are plotted on the usual arithmetical scales. It is interesting to note the transparency for energy of λ2970 for the different amounts of impurity. It is evident from these data that the production of suitable glass for artificial sunlight (with a short-wave limit of transparency near λ2800) is largely a matter of obtaining iron-free materials and keeping the iron out.

Although a discussion of the chemistry of glasses is beyond the scope of this book, some glimpses into the subject should be helpful in rounding out the treatment. Through many years we have been interested not only in the spectral transmission of all available glasses, colored and colorless, but we have developed a number of special glasses and years ago began a fundamental study of the ingredients for ultraviolet-transmitting glasses. In this work we have had the co-operation of W. M. Clark and C. D. Spencer. As a preliminary study, the spectral transmission of many natural and artificial substances was determined. This made it possible to separate the chemical elements and compounds into those which transmitted ultraviolet radiation very well and those which did not. Some results were published elsewhere [2] and a brief summary of others is presented herewith. The author acknowledges the excellent work of L. L. Holladay, a colleague, in the development of ultraviolet-transmitting glasses.

In Table XIV the short-wave limits of transparency are given for a number of compounds. A similar tabulation was made for many glasses of known composition. As a result of an analysis of such data a working hypothesis was developed to the effect that, in general, the lower the atomic number or the smaller the atomic weight of each chemical element

entering into the composition of the glass, the greater the possibility of the glass having a high transmission-factor for ultraviolet radiation. It appeared that, with few exceptions, calcium (the twentieth element in the atomic series) was about the highest one that would prove suitable for incorporation in an ultraviolet-transmitting glass. Subsequent work indicated that this general hypothesis was in the main correct. Zinc and

TABLE XIV

THE SHORTEST WAVELENGTH OF ULTRAVIOLET RADIATION TRANSMITTED BY VARIOUS SUBSTANCES OF APPROXIMATELY ONE MILLIMETER IN THICKNESS

	Limit of Transmission
Fluorite, CaF_2	λ1250
Topaz, $(AlF)_2$ SiO_4	1575
Quartz Crystal, SiO_2	1600
Potassium Chloride, KCl	1610
Gypsum, $CaSO_4$ $2H_2O$	1700
Boric Oxide, B_2O_3	1700
Colemanite, $2CaO$ $3B_2O_3$ $5H_2O$	1750
Potash Alum, Al_2 $(SO_4)_3$ K_2SO_4 $24H_2O$	1750
Soda Alum, $Al_2Na_2(SO_4)_4$ $24H_2O$	1750
Rock Salt, $CaCl_2$	1750
Celestite, $SrSO_4$	1700
Barium Sulphate, $BaSO_4$	1750
Water, H_2O	1729
Iceland Spar, $CaCO_3$	2000
(Media of Various Thicknesses)	
Window glass, 50 samples, 1 to 7 mm.	3059 to 3200
Optical lenses, 1 to 10 mm.	3200 to 3500
Celluloid, 0.2 mm.	2929
Photographic film, 0.1 mm.	2562
Paraffin, 0.2 mm.	2185
Mica, 0.1 mm.	2929
Fused borax, 2 to 8 mm.	2327 to 2628
Phosphoric acid, 3 to 6 mm.	2750 to 2874
Canada balsam, 0.1 mm.	3300
Gelatin, 0.1 mm.	2000

barium are less absorbent of ultraviolet radiation than might have been expected from this generalization but possibly not so when viewed in connection with the periodic table of the elements.

The details of composition are of interest only to the glassmaker but some comments are not out of place. Out of one series of 55 melts of different ingredients and proportions of

them 27 different specimens (varying from 2 to 5 mm. in thickness) had short-wave limits of transparency shorter than λ2600. Nineteen different specimens of the same range in thickness transmitted at least to λ2500. Sixteen exhibited short-wave limits of transparency at least as short as λ2400. Eight transmitted as far as λ2300 and two specimens 3 mm. thick transmitted as far as λ1860. This indicates the value of the hypothesis and also shows that, as far as ingredients are concerned, ultraviolet-transmitting glass can readily be made with any desired spectral range for the production and utilization of artificial sunlight.

Many interesting differences arise. For example, two glasses of the same batch composition transmitted as far into the ultraviolet as λ2400 and λ2800, respectively. Apparently the difference was due to heat treatment or purity of the constituents. Another example is that of two glasses of identical batch composition which were melted on different occasions. The minimum wavelength of radiation transmitted by one glass was λ2200 and that by the other was about λ3000. Upon chemical analysis by C. D. Spencer one was found to contain 0.057 per cent of iron oxides with a negligible amount in the ferric form and the other glass was found to contain 0.257 per cent of iron oxides with about 46 per cent of it in the ferric form.

A few of the simpler highly transparent specimens (three millimeters in thickness) and their short-wave limits of transparency are as follows:

$70B_2O_3$ $30CaF_2$	λ1850
$57SiO_2$ $43BaO$	2100
$66B_2O_3$ $30CaF_2$ $4Al_2O_3$	2260
$50SiO_2$ $50BaO$	2310
$69B_2O_3$ Na_2O	2330
$72SiO_2$ $12Na_2O$ $16CaO$	2370
$34SiO_2$ $9B_2O_3$ $13Al_2O_3$ $5CaO$	2400
$68SiO_2$ $30B_2O_3$ $32Al_2O_3$ $20CaO$	2400
$78SiO_2$ $22K_2O$	2450

S. and J. Sugie [26] found that P_2O_5 did not affect the ultraviolet transmission of glasses but that Sb_2O_3, TiO_2 and Fe_2O_3

decreased it markedly. In working with glasses transparent to ultraviolet radiation but opaque to visible radiation it was found that nickel increases the transparency to ultraviolet radiation up to a certain point. Cobalt was found to act likewise, partially verifying our discovery years ago. According to their work soda, Na_2O, may generally replace potash, K_2O_3, without materially affecting the ultraviolet transmission of glasses. In soda-lime glasses they found ferric oxide lowered the transmission more than ferrous oxide but in potash-lime glasses the effects of these oxides differed slightly. In three-component glasses consisting of $6SiO_2 \cdot 1N_2O \cdot 1Mg$ (or Ca, Zn, Sr, Cd, Sb, Ba, Pb) the transparency to ultraviolet radiation varied inversely as the atomic weights of the bivalent metallic elements. They also found that the ultraviolet transmission of glasses having five to nine components decreases as the atomic weights of the metallic elements increase.

In general, increases in the amount of lead, as in flint glasses, move the short-wave limit to longer wavelengths. This is illustrated in Table XV for glasses used in optical instruments. The increase in lead results in an increase in the refractive index and a decrease in transmission of ultraviolet radiation.

TABLE XV

THE SHORT-WAVE LIMIT OF TRANSPARENCY OF OPTICAL GLASSES AND THEIR REFRACTIVE INDEX

(Thickness, 2 mm.)

	Refractive Index	Short-wave limit of transmission
Common glass	....	λ2950
Light crown	1.51	2950
Extra light flint	1.54	2980
Medium crown	1.52	3000
Light flint	1.57	3050
Medium flint	1.62	3150
Extra dense flint	1.69	3350
Schott's heavy flint	....	3400

During recent years many glasses have been introduced commercially for the purpose of transmitting biologically-active radiation through windows and as filters for artificial sources

of ultraviolet radiation. In Fig. 25 the spectral transmission-factors are presented for a dozen commercial glasses and fused quartz two millimeters in thickness. Some of these data are taken from the work of Coblentz and Stair.[3] Inasmuch as most of these glasses transmit only a part of the energy between λ2800 and λ3200, the thickness is an important factor. A glass may be unsuitable at a thickness of several millimeters, as is necessary for filters in the form of plates, but may be quite suitable for lamp-bulbs which need be only a fraction of a millimeter in thickness.

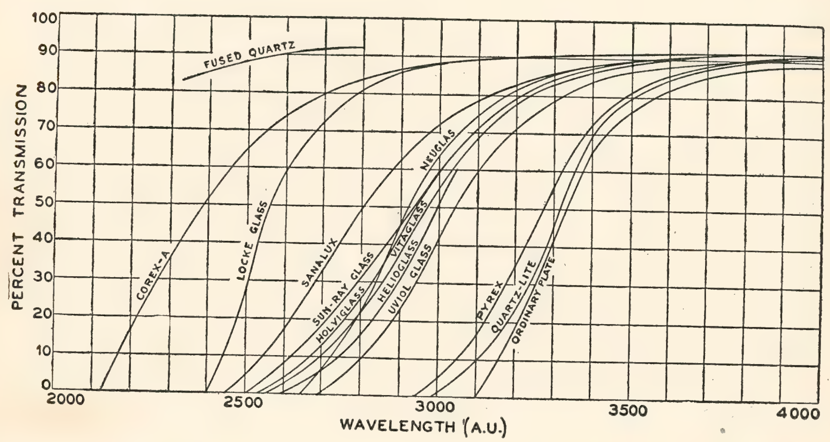

FIG. 25. Spectral transmission of a dozen commercial glasses.

In Table XVI various facts pertaining to the dozen commercial glasses (Fig. 25) are presented, including the per cent ferric oxide, the short-wave limit of transmission and the transmission-factors at λ2900 and λ3200. Notwithstanding the diversity of ingredients the short-wave limit of transparency recedes toward longer wavelengths, in general, as the content of iron oxide increases. The transmission-factors at λ2900 and λ3200 decrease, in general, as the iron oxide increases. Owing to the variation of ingredients in transparency to ultraviolet radiation it would not be expected that the short-wave limit or transmission-factors at λ2900 and λ3200 would vary exactly in accordance with the amount of iron oxide present.

However, even Table XVI emphasizes the great influence of iron as an impurity.

It should be emphasized that the data presented in this chapter are for new glasses and, therefore, do not take into account any effects of so-called solarization. Nearly all glasses lose some of their transparency to ultraviolet radiation due to exposure to this radiant energy. A glass must be reasonably permanent to be satisfactory for use in the production and utilization of artificial sunlight. This defect, its causes and remedies, are discussed in a later chapter.

TABLE XVI

MINIMUM WAVELENGTH OF RADIATION TRANSMITTED BY NEW SPECIMENS OF VARIOUS COMMERCIAL GLASSES OF 2 MM. THICKNESS; THEIR TRANSMISSIONS AT WAVELENGTHS OF λ2900 AND λ3200; AND THEIR TOTAL CONTENT OF IRON EXPRESSED AS Fe_2O_3

	Per cent Fe_2O_3	Minimum wavelength transmitted	Per cent transmitted at wavelength	
			λ2900	λ3200
Fused quartz	....	1850	92	92
Corex A	0.012	2130	87	90
Locke glass	....	2400	86	90
Sanalux glass	0.021	2450	63	83
Sun-Ray glass	0.035	2500	45	79
Holviglass	0.022	2540	42	79
Vitaglass	0.026	2550	38	78
Helioglass	0.041	2590	30	82
Corex D	....	2600	40	84
Neuglas	....	2650	45	82
Uviol glass	0.028	2680	22	71
Pyrex glass	....	2900	0	35
Quartz-Lite	0.054	3000	0	22
Ordinary window-glass	....	3100	0	17

The sloping characteristic of the spectral-transmission curves shown in Fig. 25 is common to most colorless transmitting media. Unfortunately, most glass begins to decrease rapidly in transparency at λ3200 or even λ3100. Therefore, in the spectral region of the biologically-active rays they are not transmitting maximally. Furthermore, any solarization or increase in thickness above normal, or above that necessary, results in a reduction in the efficacy of transmission of the desirable radiant energy.

All clear colorless glasses have a transmission-factor of about 90 per cent throughout the visible spectrum and all satisfactory so-called ultraviolet-transmitting glasses exhibit this high transmission-factor into the ultraviolet as far as about λ3500. Therefore, with this point in mind and also the slope of the spectral-transmission curve on the long-wave side of the absorption band of the glass, a fairly satisfactory estimate of the efficacy of a glass is obtained from the transmission-factor for energy of any wavelength in the vital spectral region. The wavelengths, λ2967 and λ3024, are suitable for this purpose because they are near the maximum of erythemal and anti-

TABLE XVII

TRANSMISSION-FACTORS OF VARIOUS GLASSES AT λ3024, WHEN NEW AND AFTER EXPOSURE TO ULTRAVIOLET RADIATION

	Thickness mm.	Per cent transmitted at λ3024 New	Solarized	
Corex A	2.95	88	82	..
Corex D	2.00	63	..	61
Helioglass	2.00	58	46	37
Holviglass	2.47	39	36	31
Locke	2.45	86	83	64
Neuglas	2.42	62	60	50
Sanalux	2.71	41	26	15
Sendlinger's	2.10	57	53	50
Sunlit	1.92	65	46	38
Uviol-Jena	2.02	61	55	43
Vitaglass	2.23	47	30	21
Vitaglass	2.00	65	..	34

rachitic effectiveness. Coblentz who has done such excellent work over many years has presented spectral-transmission curves of many transmitting media. He and Stair [3] have published an extensive summary of their work from which the data in Table XVII have been abstracted. Representative glasses from a great array of them have been chosen for this view of the media available. In order to conserve space an idea is given of the effect of exposure to solar radiation or to the radiation from a quartz-mercury arc. Of course, some of these glasses may have been improved since the data were obtained and there may be variations from batch to batch as is

commonly the case. Therefore, the solarization data are presented more as a general view than as an accurate detail. The transmission-factors for solarized glasses are indicated by two figures, the first being after exposure to the sun for several months and the second after exposure to the quartz-mercury arc at a distance of 10 cm. for 10 hours. These values are to be considered incidental here and will be discussed more fully in a later chapter. Other data pertaining to the transmission of materials are presented in later chapters. (See Plates V-VII; also Tables in Chapter XIII.)

Various substitutes for glass have been developed in recent years for use in poultry houses, solariums, etc. Some of these are sufficiently satisfactory to recommend them for special uses. Their usefulness is chiefly for admitting sunlight and it is not likely that they will be of appreciable value in dual-purpose artificial lighting.

Loosely woven cotton cloth impregnated with paraffin transmits well into the middle ultraviolet, but very inefficiently. A thin layer of paraffin transmits about 20 per cent of the ultraviolet radiation longer than λ2600. However, the diffusion of the cotton fibers permits only a small per cent of the incident ultraviolet energy to pass through. Such a cloth has some value when and where direct sunlight is of high intensities, but probably is of little value during the winter when the intensity and vital rays of sunshine are relatively low in quantity.

Various cellulose compounds have been developed and used as substitutes for glass in windows. Pure cellulose transmits 60 to 70 per cent in the region from λ2800 to λ3200. Pfund [36] found that cellophane—a regenerated cellulose used in the manufacture of artificial silk and transparent wrappings—transmits 60 per cent at λ2800 and 75 per cent at λ3200. This has been developed into a moisture-proof material of slightly less transparency. Cellulose products become more or less yellow upon exposure to ultraviolet radiation which reduces their transparency. Pfund found that cellophane depreciated least among five cellulose compounds and nitrocellulose most. The

cellulose products are practically opaque at λ2800 even when new and their transparency at λ2900 diminishes at different rates upon exposure to sunlight.

Celoglass is a trade name for a wire mesh filled with a thin layer of cellulose acetate. The mesh obstructs about 30 per cent of the radiant energy. Coblentz and Stair found it to transmit about 35 per cent of the energy at λ3200 and that the transmission decreased rapidly to zero at about λ2700. Cellulose nitrate transmitted about 24 per cent at λ3200 and dropped rapidly to zero at about λ2870. Both these decrease in transparency upon exposure to sunlight and weather but transmit appreciably in the biologically-active region of the spectrum even after months of such exposure.

Gelatin transmits quite well in the region of λ2800 to λ3200 and has recently been developed with a wire-mesh reinforcement. Of course, gelatin has been successfully used for emulsions in photographing most of the ultraviolet spectrum, which testifies to its transparency in thin layers.

Coblentz and Stair examined some new condensation products of formaldehyde and urea sold under the trade name, Aldur. They found a colorless specimen to have a high transmission throughout the ultraviolet. For such a sample Cist obtained a transmission-factor of 66 per cent at λ3024 and 48 per cent at λ2540. The latter was reduced to about 40 per cent upon exposure to the quartz mercury arc for 18 hours. New products may find new opportunities in the utilization of artificial sunlight.

Tracing cloth may have some special applications inasmuch as it transmits about one-fourth of the ultraviolet radiation between λ2500 and λ3100. When the sizing is removed the transmission drops to about 15 per cent which is the order of magnitude of the diffuse transmission of thin fabrics. Coblentz found the transmission-factors for biologically-active rays to be 21 per cent for balloon fabric, 31 per cent for nainsook and 16 per cent for batiste.

The transmission of ultraviolet radiation by woven fabrics depends chiefly upon the looseness of the weave. A closely

woven fabric must depend chiefly upon the transparency of the fibers. The amount of ultraviolet radiation which they transmit depends upon their size and composition. For ordinary white or colorless fabrics the fibers transmit less than 20 per cent of the ultraviolet radiation. Some measurements indicate that the transmission of silk and cotton fibers may approach 20 per cent and that of linen and rayon may approach 12 per cent. The open-weave fabrics such as voile and georgette crêpe may transmit as much as 50 per cent of the incident ultraviolet radiation through the interstices. Such materials along with sheer hosiery will give women an additional advantage over men in their present garb in a general use of artificial sunlight for dual-purpose lighting.

CHAPTER VIII

Infrared Radiation

As the wavelength of radiant energy increases from the ultraviolet, through the visible and into the infrared region, the photochemical activity decreases. Ultraviolet radiation is an active agency in many photochemical reactions and in producing several known biological effects. Even the short-wave visible radiation is fairly active in photochemical effects. As a consequence, the term "actinic rays" has been applied to the spectral range from the middle of the visible spectrum throughout the region of shorter wave-lengths and over most of the ultraviolet spectrum. Photographic action or the blackening of silver compounds is chiefly responsible for the term, actinic rays. However, as scientific research extended the known spectrum into the ultraviolet region where air is opaque and finally discovered Röntgen rays, the spectral range of actinicity increased. Now the term is indefinite and often misleading.

Relatively fewer photochemical effects are produced by the long-wave visible radiation but some are known even for the short-wave infrared. However, from a biological viewpoint visible and short-wave infrared are not yet of interest from a photochemical viewpoint but that they have therapeutic and tonic value is no longer in doubt. Such value as they are known to possess seems to be due to their penetration of bodily tissue. By expanding the blood capillaries, stimulating the sweat glands and warming the tissue at a depth they augment the normal bodily processes. Although other effects may be discovered eventually, the known action of long-wave visible and short-wave radiant energy is that of heating. Hyperemia is produced and excess blood-supply is beneficial in the case of many minor ailments and is of value even to those in normal health. Furthermore there is a soothing effect resulting in

relaxation. In other words, such radiations perform the functions of other heat applications generally with less inconvenience and discomfort than the usual mustard plasters, hot-water bags, hot towels and hot baths.

In the production of artificial sunlight for dual-purpose lighting the infrared radiation is not comparable in importance with the biologically-active radiation. In fact, the infrared will be accepted just as it happens to accompany the visible and vital radiant energy. Nevertheless, artificial sunlight will become more important in professional therapy, in home-treatment and in health-promotion in gymnasiums and other places so that an understanding of the infrared is desirable. Already the heating of bodily tissue is an important aim of professional therapy and thousands of simple devices are being sold for home-treatment of disorders which are painful, such as neuritis, rheumatism, etc. Furthermore, the belief is increasing among medical authorities that penetrating radiation and the effects of heating bodily tissue at a depth are beneficial accompaniments to the action of ultraviolet radiation. Certainly infrared radiation of the shorter wavelengths is present in sunlight in large quantities and, excepting for over-exposure resulting in heat-stroke, is beneficial. Owing to the enormous intensities of solar radiation and the time required for a serious sun-stroke (actually heat-stroke) there is little danger of obtaining a serious effect with an artificial source.

Progress in the scientific development of radiation therapy has been retarded by insufficient consideration and understanding of physical science on the part of investigators and practitioners. Radiant energy or radiations of all kinds—infrared, visible, ultraviolet, Röntgen—are tools which can be adequately described only by physical units such as wavelength and intensity. The chief factor, in fact the only inherent characteristic of radiant energy, is wavelength. For heterogeneous radiant energy the only inherent fundamental characteristic is the spectral distribution of energy. The properties of radiant energy vary enormously with wavelength so that spectral character is fundamenally of sole importance. There is so little

general understanding of this matter that it appears advisable to elaborate somewhat even upon the discussions of infrared radiation which have been presented in other chapters. (See Figs. 8-10.)

There is some confusion of terms. For example, deep therapy is a term applied to the use of highly penetrating gamma and Röntgen rays. However, visible and short-wave infrared radiation also penetrate bodily tissue to considerable depths. Therefore, deep therapy is a term sometimes applied to their use in heating subcutaneous bodily tissue. There need be no confusion or misunderstanding when the type or spectral range of radiation is included with the term and there is no established monopoly in the use of the term, deep therapy, for any type of penetrating radiation. Furthermore, the purpose or objective of highly penetrating gamma and Röntgen rays is so different from that of short-wave infrared that there need be no confusion at all. In the present discussion, deep therapy will mean heating at a depth with the long-wave visible and short-wave infrared which penetrate the bodily tissue effectively as compared with ultraviolet and long-wave infrared radiant energy. (See Fig. 33.)

This kind of deep therapy is now practiced with a large assortment of devices emitting radiations of vastly different wavelengths covering a wide range of the spectrum. All of them cannot be most suitable for heating at a depth in the human body. Among these are many incandescent radiators ranging from relatively low-temperature carbon filaments to high-temperature special tungsten filaments. These are enclosed in bulbs of various colors or spectral-transmission characteristics. Among these are red, yellow, blue, violet and purple bulbs. Besides these there are various non-luminous radiators in use—devices heated electrically to temperatures lower than those of incandescence. It is obvious to anyone familiar with the physical aspects that most of these devices are made, recommended, and used without much knowledge of the wavelengths of radiation involved and in some cases without even a vague conception of the physics of the subject.

Here we often find a good example of the correctness of the old adage to the effect that a little knowledge is dangerous. Vaguely it is known by many that radiation consists of "vibrations." Therefore, mysterious and even metaphysical ideas are entertained in regard to the effect of these vibrations upon human ailments. Even these vague ideas are not monopolized by the questionable practitioners but, owing to lack of knowledge, are entertained by some medical men of unquestionable character and standing.

One known fact of infrared therapy is heating at a depth. No other fundamental cause of beneficial results is known. No direct influence of wavelength upon curative value has been found as in the case of ultraviolet radiation. Therefore, at least the physics of the subject must deal with that of the absorption of radiation by the bodily tissue. Knowledge of this aspect clarifies much of the confusion now existing in regard to infrared therapy.

Heating can be done by radiation, convection, and conduction. When a hot towel is placed upon the skin, heating at a depth is accomplished almost solely by conduction. The skin in contact with the towel may be the hottest part of the body. Some heat from the towel is lost by radiation and conduction outward. If air comes into contact with the towel, it is heated and convection currents of air carry this heat away. The liquids of the body carry some heat away by their movement, but this is not true convection and at best is perhaps a small part of the effect of the hot application.

If an electric filament lamp is held close to the body, some radiant energy enters the body. On being absorbed it is converted into heat and heating at a depth is achieved without direct contact with the hot bulb as in the case of a hot towel. Not only is this more comfortable for the patient, but greater heating at a depth can be achieved by the absorption of the radiant energy than by direct conduction. In a consideration of the physics of heating by absorption of radiant energy or radiation, it is only necessary to know the spectral transmission of the body. This is not known in actual detail but enough

is known to bring order out of the present chaos. In fact, it is practicable to consider the spectral transmission of the human body to be similar to that of water, of which it chiefly consists. The present state of the art of infrared therapy and the uncertainty of measuring the results of it do not require any greater accuracy of assumption than the foregoing. However, we may be guided further by the fact that blood transmits infrared somewhat as red-tinted water does. The conclusions drawn in this paper would not be altered in general, and only relatively slightly in detail, if exact spectral transmission-factors of the elements of the human body were available. These conclusions will show how inconsistent the claims for the various radiators are and that many must be ruled out of consideration if the greatest heating at a depth is desired and if the greatest efficiency is a consideration.

That the human body is somewhat transparent to visible radiation is readily demonstrated by holding the hand over a light-source such as a flash-light. In the dark the hand is seen to transmit considerable light or visible radiation. It is seen that the color of the light is only a tint of red. This indicates that much of the radiation throughout the spectrum—including violet, blue, green, and yellow rays—passes through the hand. Therefore, radiation of all wavelengths in the visible region may be considered to be more or less penetrating and useful in deep therapy. If we replaced the eyes with an instrument sensitive to the near infrared, some of these invisible radiations would be found to pass through the hand. Years ago in connection with a study of infrared and the eye,[31] certain computations were made which are applicable to the present problem. In addition to these, certain modern sources have been considered, so that a view may be obtained of present radiators of a great range in temperature.[10] Water transmits radiant energy of all wavelengths throughout the visible and only partially in the near infrared region. Pure water is transparent to ultraviolet energy throughout most of its spectral extent, but, inasmuch as ultraviolet radiation is insignificant when measured as energy, this region is not considered here-

with for heating at a depth. Besides, the salts and colored compounds in the bodily tissue absorb most or all of it.

In Fig. 26 the transmission-factors of four different thicknesses of water are given for radiant energy of various wavelengths throughout the visible and near infrared regions. It will be noted that a thickness of 2.28 cm. of water (nearly an inch) is (1) transparent to radiations of wavelengths corresponding to the visible spectral region, (2) only partially transparent to radiations in the near infrared, and (3) is totally opaque to radiations of longer wavelengths than λ14000. The visible spectrum lies between approximately λ4000 and λ7600.

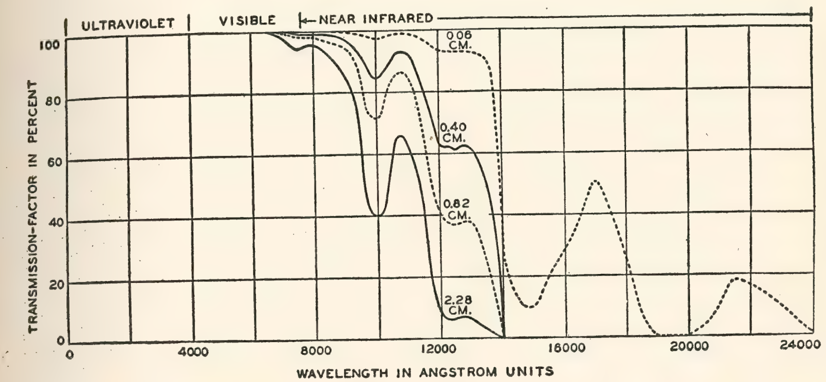

FIG. 26. The transmission-factors of radiant energy of various wavelengths—throughout the visible and near infrared regions—are presented for water of four different thicknesses.

The ultraviolet extends from λ4000 toward shorter wavelengths. The infrared extends from λ7600 toward longer wavelengths. Although a layer of water 2.28 cm. in thickness is completely opaque to infrared energy greater than λ14000, a layer 0.06 cm. in thickness transmits partially out to λ25000 but is opaque to wavelengths longer than this until λ80000 is reached. This latter region is discussed later.

Such data as the foregoing prepare us to consider the relative value of radiators of various temperatures. In Fig. 27 are shown the spectral distributions of energy as emitted by seven incandescent solids. The black-body is a theoretical

source emitting radiant energy in accordance with fundamental physical laws. Incandescent carbon and tungsten do this approximately. It is seen that as the temperature increases a relatively greater percentage of radiation is emitted in the visible and near infrared. The areas contained within the curves and the common base-line represent relative amounts of total energy emitted by the sources at the color-temperatures indicated. In this case these areas are the same for all

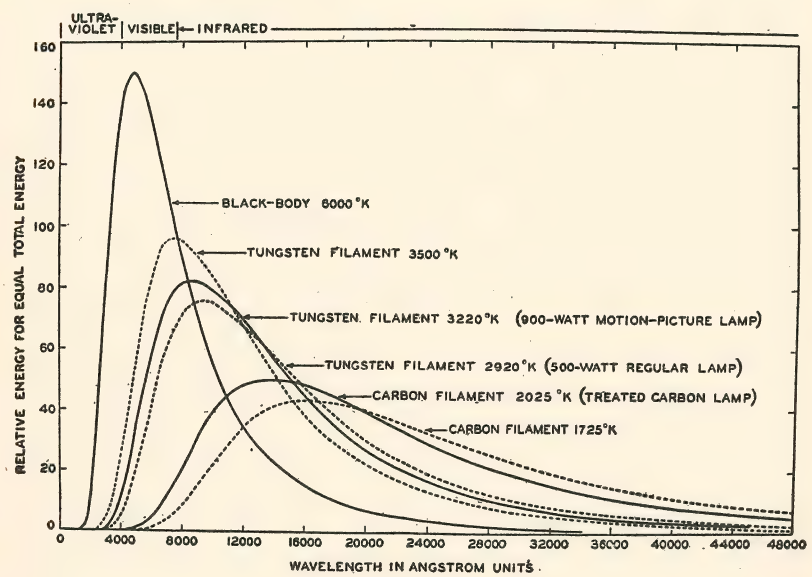

FIG. 27. The spectral distributions of energy from seven incandescent solids of different color-temperatures (Kelvin scale). The total radiant energy emitted is the same for all these radiators. As the temperature increases the amount of energy emitted in the visible and near infrared regions increases.

the curves which means that the total energy emitted by each source is identical with that emitted by each of the others. The ratio of the area between any two wavelength vertical lines, to the total area, is the percentage of the total energy in any case emitted within this range of wavelengths. It is seen that, as the temperature increases, a greater percentage of energy is emitted by an incandescent solid between $\lambda 4000$ and $\lambda 12000$ (the region of almost complete transparency of

an inch of water). Thus we are ready to eliminate the low-temperature incandescent solids in favor of the high-temperature ones.

In obtaining heating at a depth, it is desirable to have as little absorption as possible in the first or outer layer of the body. This leaves more radiant energy to penetrate more deeply, where by absorption it is converted into heat, thereby

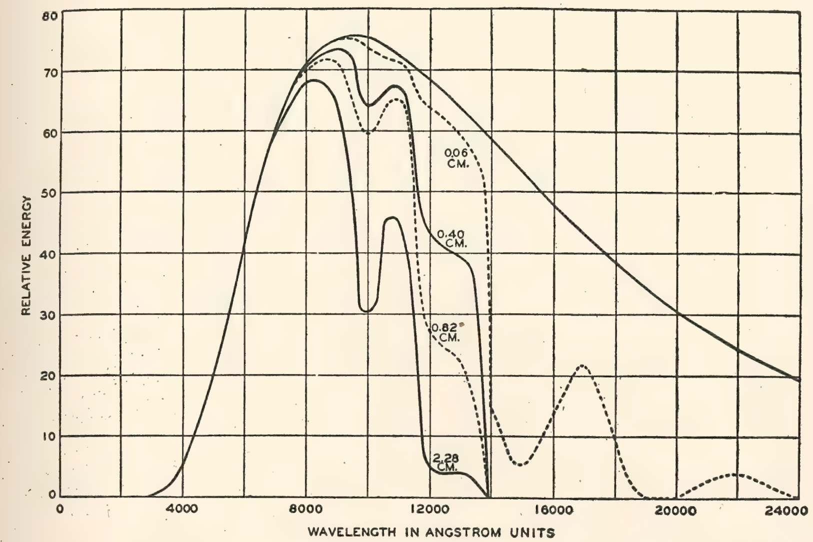

FIG. 28. The spectral distribution of energy emitted by an ordinary 500-watt tungsten lamp is shown in the upper curve. The amounts of this energy of various wavelengths which pass through four different layers of water respectively are shown by the four irregular curves. Inasmuch as the areas represent amounts of energy, the ratio of the area under the irregular curve (marked 2.28 cm.) to the total area under the uppermost regular curve indicates the percentage of the total energy which remains unabsorbed after a depth of 2.28 cm. of water is reached.

heating the deeper layer. From Figs. 26 and 27 it is seen that the maximum of the curve for a tungsten filament at 3500 deg. K (color-temperature = 3646 deg. K) is near $\lambda 7600$ or the border-line between the visible and near infrared. Therefore, much more of the energy of the wavelengths to which water is transparent, or fairly so, is emitted by this source than by incandescent solids of much lower temperatures.

Therefore, of all the actual sources considered in Fig. 27 the tungsten-filament lamps appear to be best suited for deep therapy. Any modification by means of colored bulbs decreases their efficacy by reducing the amount of radiant energy available. Why use a blue bulb to eliminate much of the yellow and red radiation which should be used in heating at a depth just as the blue radiations are? Still many blue bulbs are in use. Why use a red bulb to eliminate blue and green radiations when these are likewise valuable in penetrating the body? It is possible that in some cases it might be of advan-

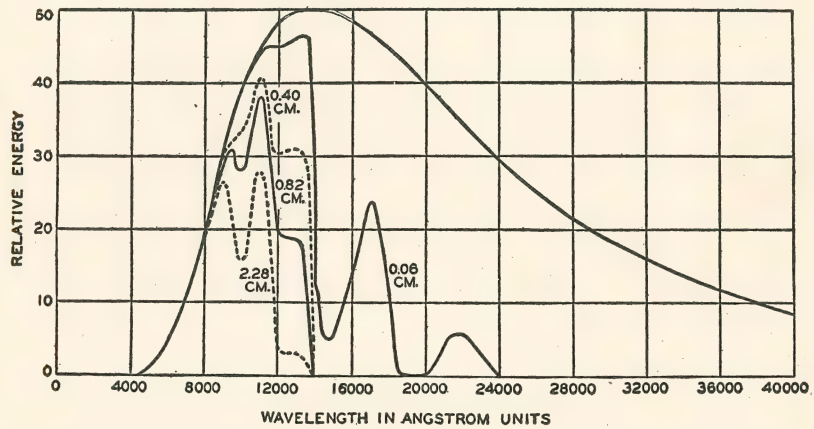

FIG. 29. The uppermost regular curve is that of spectral distribution of energy emitted by the old 4 watt-per-candle carbon-filament lamp. The irregular curves indicate the relative amounts of energy transmitted respectively by the four layers of water.

tage to use the most penetrating radiation. Equipping a high-temperature tungsten-filament lamp with a red bulb would provide this approximately. A further approach to the ideally efficient radiation for penetrating the bodily tissue to a depth would be obtained by filtering this radiation through light red glass and an inch of water.

Figs. 28 and 29 make this point clearer and at the same time indicate that an ordinary high-temperature tungsten-filament lamp is more desirable for heating at a depth in the human body than the old 4 watt-per-candle carbon-filament

lamp of much lower filament-temperature. In Fig. 28 the major portion of the spectral energy distribution of the present 500-watt tungsten-filament lamp is presented. The relative amount of energy of each wavelength transmitted by 2.28 cm. of water is shown in the lowest curve. The ratio of the area under this lowest irregular curve to the total area under the outer regular curve is the percentage of total energy trans-

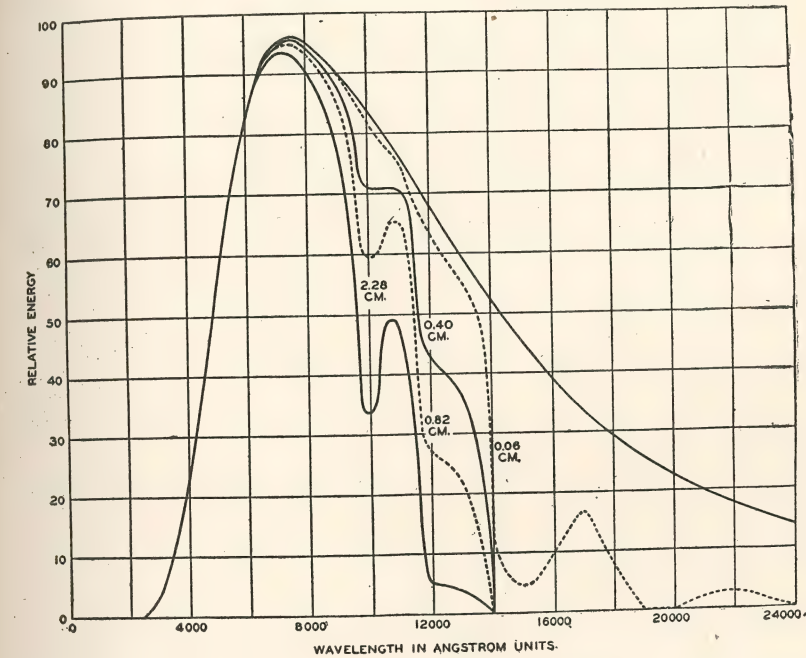

FIG. 30. Showing the spectral distribution of energy emitted by solid tungsten at 3500 deg. K (near its melting-point) and the relative amounts of energy of various wavelengths transmitted by the four layers of water respectively. The color-temperature is 3646 deg. K.

mitted by the 2.28 cm. of water. The relative amounts of energy of various wavelengths transmitted by the other three thicknesses of water are also shown and the same analysis applies to them.

In Fig. 29 the same physical basis is given for the old carbon lamp. The ratio of the area under the irregular curve to the total area under the outside regular curve (spectral

energy distribution for a 4 watt-per-candle carbon-filament) is seen to be much smaller than in the case of the 500-watt tungsten-filament lamp (Fig. 28). This means that in the case of this tungsten-filament lamp more energy remains unabsorbed after 2.28 cm. of water have been penetrated than in the case of the carbon lamp. Therefore, the former is the better radiator for heating at a depth.

The foregoing point is further emphasized by Fig. 30,

TABLE XVIII

Percentage of Radiant Energy, from Various Sources, Absorbed in Various Layers of Water. The Data Pertaining to Black-bodies Applies to Other Solid Radiators at the Same Color-temperature (See Chapter X)

Source (True Temperature)	Percentage of Total Energy Absorbed in Water of Depth				Remaining Unabsorbed at Depth of 2.28 cm.
	0.06 cm.	0.40 cm.	0.82 cm.	2.28 cm.	
Black-body, 2000 deg. K.........	68.8	80.6	83.8	89.7	10.3
Black-body, 2500 deg. K.........	51.7	63.3	68.3	76.7	23.3
Black-body, 3000 deg. K.........	38.5	49.8	55.7	65.1	34.9
Black-body, 4000 deg. K.........	22.8	31.7	37.2	45.9	54.1
Black-body, 5000 deg. K.........	13.0	19.6	23.4	30.4	69.6
(a) Carbon filament, 2090 deg. K..	64.1	77.3	81.0	87.9	12.1
(b) Tungsten filament, 2500 deg. K	50.4	64.5	70.5	80.0	20.0
(c) Tungsten filament, 2920 deg. K	46.5	58.0	62.2	70.5	29.5
(d) Tungsten filament, 3500 deg. K	33.6	43.6	48.4	56.4	43.6

(a) Old treated carbon-filament; 4 watts per candle.
(b) Approximating regular vacuum tungsten lamps; 9 lumens per watt.
(c) Actually a 500-watt gas-filled tungsten lamp; 19 lumens per watt.
(d) Near the melting-point of tungsten; 46 lumens per watt.

in which the source of radiation is tungsten at 3500 deg. K—near the melting-point. Here it is seen that the area under the lowest irregular curve (which shows the spectral transmission of 2.28 cm. of water for the radiation from this source) is a still larger percentage of the total energy emitted by the source than in the case of Fig. 28. This indicates that for deep thermal effectiveness the best available source of radiant energy is a solid of high temperature. Of the electric filament-lamps, the high-efficiency tungsten lamps are seen to provide

the most effective energy for heating bodily tissue at a depth. Furthermore, there is nothing known which leads to the belief that this will have to be altered when all details of heating the depths of the body are known.

In Table XVIII the amounts of energy absorbed in layers of water of four thicknesses are presented for theoretical black-body radiators and for four practical sources of various temperatures. The percentages of total radiant energy absorbed in four layers of water, respectively, are given in the first four columns of figures. In the last column are the percentages of total energy remaining unabsorbed from various sources of radiation after passing through 2.28 cm. (0.9 inch) of water. It is seen that as the temperature of the source increases, the percentage of unabsorbed energy increases. Inasmuch as the source having the lowest temperature is incandescent, non-luminous radiators are not under consideration in this comparison. Furthermore, it is seen that, of the practicable incandescent sources available, the regular high-efficiency gas-filled tungsten lamps are the more efficient producers of penetrating radiant energy. If any bulb besides a colorless one is used, the value of the lamp for deep therapy would be reduced whether the bulb were blue, violet, purple, red or any other color. The energy of wavelengths not as penetrating as others is absorbed by the superficial layers and contributes to the total heating effect. In general the bodily tissue acting as a filter becomes heated by the absorbed energy. The energy absorbed by a colored bulb does not contribute to the heating effect. Of course, where the heating of superficial layers is to be minimized the red glass and water-cell could be used. However, infrared therapy does not have sufficient scientific basis to require such refinements for general use.

Inasmuch as the body consists largely of water, these values and conclusions are indicative of the actual and tenable ones. Any salts in solution cannot appreciably alter the general conclusions or the order of rank of these sources. Finally the general reddish tint of the bodily tissue cannot possibly reverse the order of rank. Of course, the bodily tissue is a diffusing

medium which scatters the radiant energy more or less but this does not alter the values relative to each other.

Fig. 31 presents a graphic view of the data found in Table XVIII. This further emphasizes the superiority of high-temperature incandescent solids over low-temperature ones for penetrating water, or on the reasonable assumption upon which this discussion is based, for thermal effectiveness in the depths of bodily tissue. Here the horizontal scale is thickness of water in centimeters and the vertical scale is in percentage of energy transmitted. For any given source the energy trans-

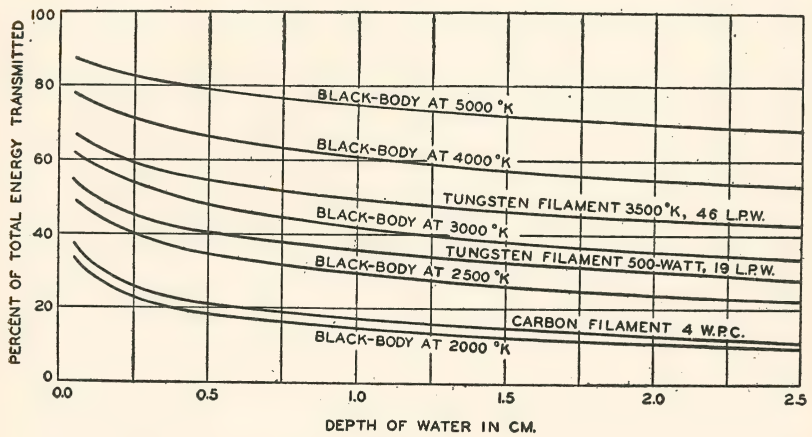

FIG. 31. Showing the relation between the transmission-factor, or total energy transmitted, and the thickness of water for the sources considered in Table XVIII.

mitted decreases with thickness—rapidly at first, then more slowly. It is seen that as the temperature of the source increases the curve is located higher in the diagram, indicating that water is more transparent to radiations from high-temperature sources than from low-temperature ones.

In Fig. 32 are presented the percentages of total energy absorbed by layers of water at various depths for incandescent solids of different temperatures from 2000 deg. K to 5000 deg. K. The practicable incandescent-solid sources are within this range as seen in Figs. 27 and 31. It will be noted that the first layer, even though it is only 0.06 cm. in thickness,

absorbs considerable of the total energy. The next layer (from depth 0.06 cm. to depth 0.40 cm.) absorbs about twice as much of the total energy as the next layer (from depth 0.40 cm. to 0.82 cm.) which is slightly thicker. By consulting the other layers it is seen that the absorption of successive layers of equal thickness diminishes rapidly. In fact, this absorption follows a well-known law.

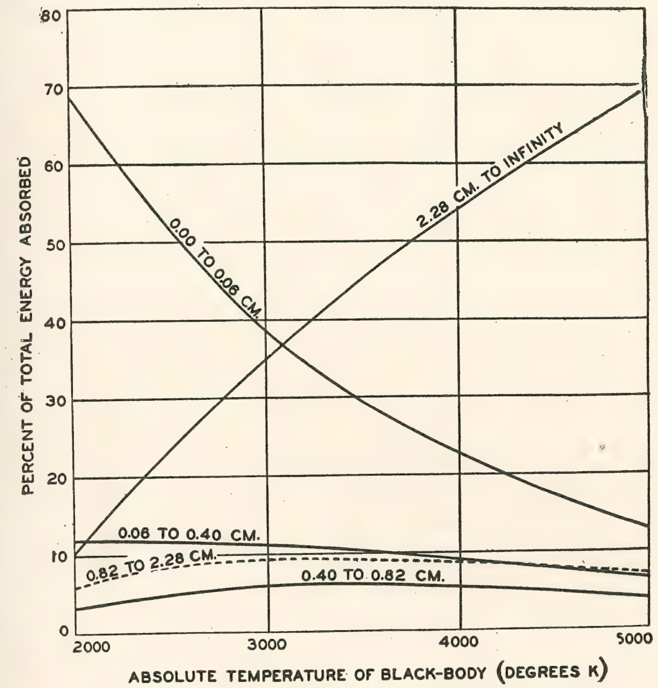

FIG. 32. The percentage of total energy absorbed by water of various depths depends upon the temperature of the source of the radiant energy.

The intensity of radiation of any given wavelength after traversing any given depth d can be computed from the equation,

$$I = I_0 e^{-xd}$$

where I_0 and I are the original and the final intensities, respectively, e is the base of Naperian logarithms, and x is the

extinction-coefficient. This can be further simplified for the purposes of computation into,

$$log\ T = -\ xd\ log\ e$$

where T is the transmission-factor, e equals 2.7183, and $log\ e$ equals 0.4343. If I_0 is taken as unity, I is numerically equal to the transmission-factor for the thickness d of the substance, for radiant energy of a given wavelength. In this manner many computations can be made throughout the spectrum and for many thicknesses of media. Years ago in connection with spectral work the writer devised a short-cut graphic method of making one set of computations or measurements answer for an infinite range of thicknesses.[42] This method is now widely used and may be of interest to those who would pursue this subject further.

In Fig. 31 it is interesting to note that as the temperature of the source increases to 5000 deg. K, the percentage of total energy remaining to be absorbed in the layer from depth 2.28 cm. to depths beyond increases. This emphasizes again that among the incandescent solids a high-temperature source is desirable. Inasmuch as temperatures of incandescent solids of 5000 deg. K or more are not practicable at present, the data are not presented for higher temperatures.

Non-luminous bodies, heated electrically or otherwise to temperatures much less than that of incandescent solids, may also be judged from the basis of physics. It is known that water is quite opaque to infrared energy from λ24000 to λ80000 and that it is transparent to radiant energy between λ80000 and λ500000—a range in wavelength represented in microns by 8μ to 50μ. In Fig. 27 it is seen that the wavelength of maximum radiation shifts toward shorter wavelengths as the temperature of an incandescent solid is increased. Conversely, the shift is toward longer wavelengths if the temperature is decreased.

The position of the maximum of the curve of spectral distribution of energy may be readily computed for the theoretical black-body from the well-known law:

$$\lambda_m T = C$$

where λ_m is the wavelength of maximum radiation, C is a constant, and T is the absolute temperature. When the wavelength is expressed in Angström units and the temperature is expressed on the Kelvin scale, the value of the constant C is 28,900,000. This is known as Wein's displacement law and the accuracy of the law may readily be tested by the reader by multiplying λ_m and T in each case in Fig. 27. When the wavelength is expressed in any other unit the constant C is varied accordingly. For this purpose it will be recalled that one micron (μ) equals 1000 millimicrons (mμ) or 10000 Angström units. The Angström unit is convenient in the ultraviolet and visible, but becomes unwieldy in the infrared where the micron is more satisfactory. However, to avoid confusion the Angström unit is used throughout this discussion.

Obviously, if non-luminous radiators are to be effective, they must radiate appreciable energy between λ80000 and λ500000 (8μ and 50μ). If they are to be efficient, much of the total energy emitted must be of wavelengths within this range. Simple computations of the wavelength of maximum radiation by means of Wein's displacement law reveal the temperatures which non-luminous radiators must have if they are efficiently to supply radiation which will penetrate the body as in the case of that emitted by incandescent solids of high temperature. The wavelength of maximum radiation must be between λ80000 and λ500000. These simple computations reveal the temperature range for such sources to be from 360 deg. K to 60 deg. K. The upper limit is 87 deg. C or about the temperature of a hot-water bag. The lower limit of temperature is —213 deg. C or 213 degrees below zero on the Centigrade scale. Hot-water bags have often been effectively used, but a source having a temperature 213 Centigrade degrees below the freezing-point of water has not

been seriously proposed by anyone, notwithstanding the fact that such a recommendation has as much scientific foundation as many of the therapeutic devices sold at a considerable price and in appreciable numbers for heating bodily tissue. Therefore, it is seen that possibilities among non-luminous sources are confined to temperatures in the neighborhood of hot-water bottles. This brings us back to the hot towels, water bottles, etc., with all their discomfort, inconvenience, and lack of accurate control which modern deep therapy can largely eliminate.

It is seen that the foregoing considerations exclude non-luminous hot radiators from the class of incandescent solids as efficient and effective sources for deep therapy. Still, there

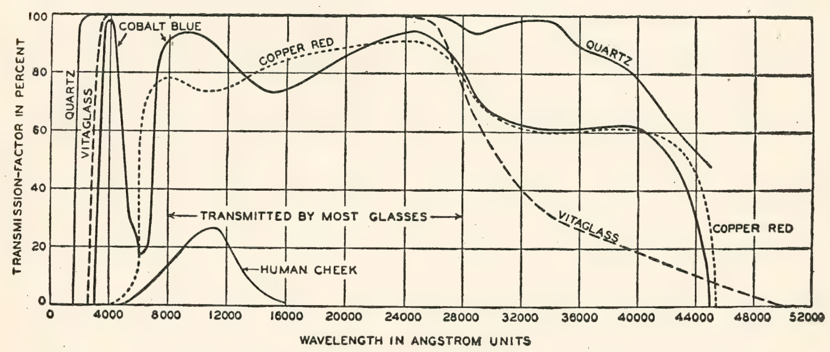

FIG. 33. The transmission-factors of representative glasses and the human cheek for radiant energy of various wavelengths.

are many costly devices of this kind in use. Whatever beneficial results may be obtained by them must result from heating the surface of the body just as a hot towel does. Actually heating at a depth, then, is achieved by the conduction of heat into deeper layers of the body. There can be little or no direct penetration of the radiant energy as in the case of radiation from high-temperature incandescent solids such as the tungsten-filament lamp.

Owing to the questions which so often arise in regard to the spectral transmission of glasses in the infrared regions, a few examples are presented in Fig. 33. It is seen that they are fairly transparent to the near infrared but that their transparency decreases in general beyond λ30000 (or 3μ). Even colored glasses have fairly high transmission-factors in the near infrared. The clear glasses, including quartz, are almost perfectly transparent out to λ28000 and quite effectively transmit energy as far as λ40000. With the exception of special glasses developed for the purpose of absorbing infrared radiation it may be generally assumed that colorless glasses are quite transparent to the near infrared.

It is emphasized again from the foregoing considerations of the physical basis of this kind of deep therapy that, of the incandescent solids, the high-temperature sources supply the most penetrating (visible and near infrared) radiation for deep therapy. The high-efficiency gas-filled tungsten-filament lamps with regular bulbs are the most efficient and should be the most effective, of all the sources considered, for heating at a considerable depth in the human body. Furthermore, it may be emphasized that special bulbs—colored or colorless—are generally unnecessary and even unjustifiable and that colored bulbs in general reduce the efficiency and efficacy of incandescent solids for heating bodily tissue at a depth because they absorb some of the penetrating radiation. These conclusions are drawn from a consideration of heating at a depth as being the primary cause of beneficial results of such therapeutic practice.

As has been stated, no photochemical action of infrared radiation has been established in regard to its effect upon bodily tissue. It is difficult to imagine that the radiation in sunlight did not acquire some intimate associations with bodily processes throughout the ages when it was a prominent environmental factor in the evolution of life. Also it is difficult to imagine that the human body, exposed to it in the early ages of primitive nakedness, cannot benefit by it. Human beings never acquired immunity from the need of air, water or food. Perhaps clothing and indoorsness are robbing human beings of some beneficial tonic effects of visible and near infrared radiations in sunlight. Certain therapeutic values have been established and so-called light-baths are beneficial in some

ways. Inasmuch as tungsten filaments at high temperatures emit appreciable amounts of biologically-active ultraviolet radiation it is possible that the best light-bath would be produced by high-temperature tungsten filaments in ultraviolet-transmitting bulbs. These would provide efficient sources of radiant energy which penetrate the bodily tissue and combine the beneficial effects of mild ultraviolet radiation.

As has been emphasized, infrared radiation in artificial sunlight is of secondary importance which does not warrant much sacrifice in producing it in proper quantities. It accompanies all practicable sources of light and ultraviolet radiation but, other factors being equal, those sources will likely be more favorably viewed which emit appreciable quantities of the radiations which penetrate deeply into bodily tissue. At least this is likely for specific uses of artificial sunlight in professional therapy and home-treatment.

The foregoing conclusions based upon work done ten years ago have been adequately verified recently by Cartwright.[43] By means of a vacuum thermocouple he measured the energy of various wavelengths which passed through the cheek and also through bacon fat. The energy maximally transmitted by the cheek is near $\lambda 11000$. The spectral transmission curve of the flesh of the cheek corrected approximately for surface reflection is plotted in Fig. 33. The transmission-factors as presented by Cartwright are not to be considered exact values because apparently the diffusion of radiation within the flesh was not taken into account. However, the spectral character of the transmitted radiation should be fairly well indicated by the method employed. In Fig. 33 the spectral transmission of the flesh of the cheek is of interest chiefly in indicating the approximate maximum and limiting wavelengths. Cartwright arrived at the same recommendations which we have advocated for years—(1) that ordinary tungsten-filament lamps are the best sources of radiation for heating bodily tissue at a depth and (2) that a red filter including a layer of water would eliminate the less penetrative radiation.

CHAPTER IX

Permanency of Materials

Throughout the development of electric lighting ultraviolet radiation was not desired excepting for special technical processes. Naturally, there was little or no incentive in ordinary lighting to produce efficient media for reflecting or transmitting ultraviolet radiation. In fact, in order to safeguard the eyes in the case of electric arcs considerable effort was directed in the opposite direction. Sometimes such effort far exceeded the necessity. Permanency of materials was of interest chiefly on account of the known deleterious effects of daylight upon glass and colored media. As a consequence, some investigations were made, such as in the fading of materials and in the deterioration of glass in windows and artificial lighting equipment. With the development of sources of ultraviolet radiation and the use of these in therapy and for health-maintenance many transmitting substances have been developed. The stability of these and of colored materials, necessarily or incidentally exposed to radiant energy, has become of great interest.

The development of the characteristic amethyst color in arc-lamp globes after prolonged exposure to radiant energy and also in skylight glass exposed to sunlight has been observed for years. Many years ago we showed [27] that such glasses could be decolorized by heating to moderate temperatures. Glasses exposed to Röntgen rays sometimes develop color, yellow and purple tints being most common. This coloration of clear glasses is not confined to those containing manganese. Sometimes glasses containing potash, but free from manganese, gradually assume a bluish tinge and those containing sodium, a yellowish color. Many other effects have been observed, but the manganese coloration is most prominent.

There are many cases of radiation of two different wavelengths or spectral ranges producing opposite effects. Apparently it is a fairly general rule that of two radiations producing opposite effects, the longer wavelengths are responsible for oxidizing action and the shorter ones produce a reducing action. The decoloration of glass by infrared, after it has been colored by ultraviolet radiation, illustrates the foregoing. We have seen cases where both actions may be going on simultaneously with little or no resultant action in a clear glass.

Manganese in clear glass performs the function of neu-

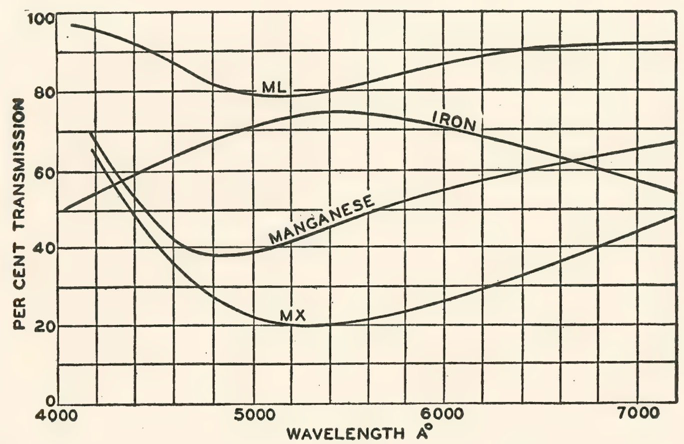

FIG. 34. Spectral transmission of glasses containing slight amounts of iron and manganese, respectively. Purplish tint developed in colorless glass by an arc-lamp and by Röntgen rays is shown in ML and MX, respectively.

tralizing the greenish tint usually present, owing to slight quantities of iron oxide in the glass as an impurity. The spectral transmissions of glasses containing slight amounts of iron and manganese, respectively, are shown in two curves in Fig. 34. It is seen that the curve for the glass containing iron is approximately complementary to that of the glass containing manganese; that is, the purplish tint neutralizes the greenish one. Although this usually makes a glass more desirable from an esthetic viewpoint, years ago we advised that its use be discontinued in street-lighting glassware and even in glassware used with arc-lamps indoors. The addition of manga-

nese reduces the transmission of light by several per cent for which no benefit is obtained in many uses of illuminating glassware. Furthermore, our measurements showed that as the purplish color was brought out by sunlight and by radiation from arc-lamps the transmission was commonly reduced from 10 to 25 per cent in cases where the color appeared to be slight. In the case of some opal glasses taken from service the reduction in luminous output was as high as 85 per cent.

The author has in his possession bottles which lay upon the desert in Death Valley for years. They are colored a very deep amethyst by solar radiation.

The spectral transmission of a clear glass in which the purplish tint was brought out by an arc-lamp is shown in curve *ML*, Fig. 34. Another specimen exposed to Röntgen rays exhibited the spectral transmission shown by curve *MX* and it transmitted only 40 per cent as much as it did when clear and colorless before exposure.

Owing to the persistence of habit it has been difficult to awaken the glass-maker to the folly of including manganese in glasses exposed to sunlight and to arc-lamps. However, the new demand for transparency to certain ultraviolet radiations should bring this about. Certainly iron must be eliminated or reduced to minute quantities. Manganese is no longer needed and it has little excuse for use excepting in those relatively few cases where esthetic considerations are important and real.

In 1917 we studied [28] the influence of temperature upon the transmission of light by various colored glasses. The source of light was a high-wattage tungsten-filament lamp and the temperature ranged from 20 to 360 deg. C. The results for ten representative colored glasses are shown in Fig. 35. In many cases the change in color is clearly visible. The principal coloring element and the color when cold are indicated in the illustration. As the temperature increased all the glasses, excepting the blue ones containing cobalt, decreased in light-transmission. Owing to the relatively slight change in hue in the red end of the spectrum and to the saturation of color of red glasses these

do not show a change in integral color. However, the amount of light which they transmit decreases markedly as their temperature increases. Owing to the difficulty of specifying the colored glasses accurately only the relative change in transmission-factors is given in each case. Furthermore, it should be obvious that these changes depend somewhat upon the spectral character of the light used.

In the development and use of colored accessories we have

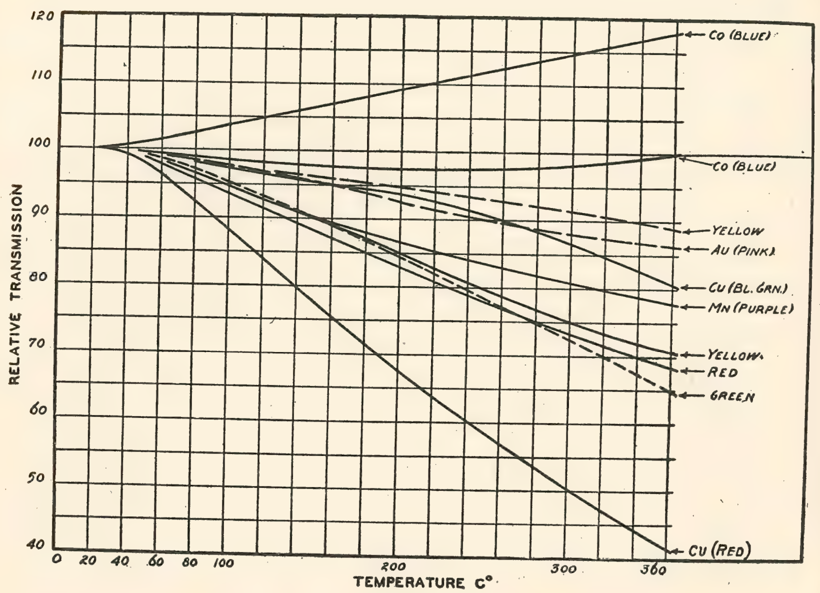

FIG. 35. Influence of temperature upon the transmission of light by colored glasses.

studied many colored media, including glass, gelatin, and superficial coatings developed. In general, their transmission changes with temperature. The change, as is seen in Fig. 35, is accounted for by a shift in the absorption band toward longer wavelengths. Usually the color and transmission-factor return to normal values at lower temperatures. In other words, excepting in the case of fading of fugitive dyes and pigments used in gelatin and superficial coatings, the change is not permanent. In fact, notwithstanding many complaints that colored glass

fades, we have not been able to establish this fact for colored glasses used with tungsten-filament lamps.

The chief result of these studies is to establish the necessity of photometering colored glass under the condition of use. This not only applies to colored-glass accessories used in lighting but also to glasses used in pyrometry and in other scientific and technical processes. The change in the light-transmission of colored-glass accessories from room temperature to that obtaining when they are used with a 150-watt tungsten-filament lamp in a housing designed for usual lighting purposes, is as follows:

Red	41 per cent decrease
Yellow	9 per cent decrease
Green	16 per cent decrease
Blue	3 per cent increase

The foregoing colors differed in degree of saturation. The red glasses are fairly saturated in color and transmit about 10 per cent of the light from a 150-watt tungsten-filament lamp. The yellow is moderately saturated and transmits about 40 per cent of the light. The green is less saturated and transmits about 5 per cent. Owing to the relatively small amount of blue light available, blue-glass accessories for lighting are frankly a compromise. They are of low saturation and transmit about one per cent of the total light.

Although colored glasses do not fade when used with radiation from tungsten-filament lamps, their transmission-factors for light depend upon their temperatures. Whether or not they are permanent or reasonably so when subjected for long exposures to intense ultraviolet radiation is not known. However, excepting in very special cases, this is not of practical interest because they will not be used with natural or artificial sunlight.

It is now generally known that most clear colorless glasses are altered in their transmission of ultraviolet radiation by their exposure to it. Usually there is a marked shift of their absorption band toward longer wavelengths. The long-wave side of the absorption band often shifts so far, under exposure

to sunlight or to ultraviolet energy from artificial sources, as to greatly reduce the transmission of biologically-active radiation and sometimes even to zero. Usually the glasses may be "rejuvenated" by heating them; that is, the absorption band shifts toward shorter wavelengths under the influence of heat, returning more or less to its position when the glass was new. The phenomenon has been termed "solarization" due to the fact that it became important first in the case of glasses for transmitting the biologically-active radiation in sunlight. No measurable recovery of a solarized glass has been discovered as yet by permitting it to remain in the dark at room temperature.

The phenomenon of solarization may be considered, from a practical viewpoint, as photostabilization. A given glass may possess different levels or stages of stability depending upon the intensity and particularly upon the spectral character of the radiant energy. The rate of change from one condition to the other depends upon the intensity of the effective radiation which, of course, is some or all the absorbed energy. A glass may continue to solarize for many months under exposure to sunlight and still may not reach the same stage as is produced by exposure of a few hours to the quartz mercury arc at a distance of a few inches. Whether or not specimens of the same glass will eventually reach the same stage of reduced ultraviolet transmission under exposures to sunlight and to the quartz mercury arc has not been determined. It is likely that they will not, owing to the radically different ultraviolet radiations absorbed in the two cases.

Coblentz [3] and his colleagues have made elaborate studies of the solarization of glasses and in other ways have contributed much valuable data pertaining to ultraviolet radiation. In Table XVII some of their data have been presented. From these representative cases it is seen that the decrease in transmission for energy of λ3024 is appreciable upon exposure to sunlight for a few months and is even greater for exposures of a day or less to a quartz mercury arc at a distance of a few inches.

An illustrative case is shown in Fig. 36. Vitaglass is the

commercial name for a glass developed by Lamplough several years ago. When new its transmission-factor is 40 per cent at λ3000—about one-half that of the ideal which is theoretically attainable. This glass is not chosen for criticism but rather as a compliment to the development and commercialization of a product which was very much needed. The specimen chosen

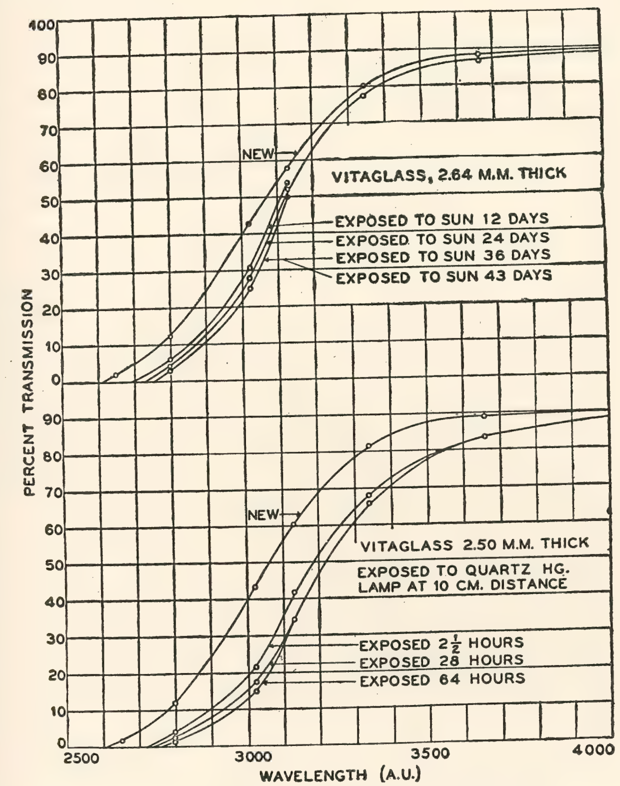

Fig. 36. Solarization of a commercial glass.

for Fig. 36 may not be representative of the product at present. In fact, there is some variation among different samples of any product of this sort. It has been shown in another chapter that small amounts of iron oxide as an impurity make great differences in the transmission in the ultraviolet region. This and thickness, and perhaps heat-treatment and other variables, account for the differences.

In Fig. 36 it is seen that after a month of exposure to the sunlight the specimen had reached a stage of photostability or at least a point where the solarization proceeded slowly. After an exposure of one day to the quartz mercury arc even a lower stage had been reached. The ultraviolet radiation from the quartz mercury arc, as measured by the production of erythema, is 600 times more effective per footcandle than midsummer sunlight. At 10 cm. from the quartz mercury arc a given degree of erythema should be produced by an exposure considerably less than one per cent of that required by midday midsummer sunlight. In fact, on this basis the exposure to sunlight would have to be about 160 times as long as that at 10 cm. from the quartz mercury arc. However, the erythemal basis very likely appraises the short-wave ultraviolet between λ2800 and λ2200 less than it should be as a photostabilizing agency in the solarization of glass. Therefore, it is possible and even likely that the condition of exposure to the mercury arc is hundreds of times more powerful in producing solarization than the best summer sunlight.

Another important illustrative case is shown in Fig. 37 for Corex glass which is a prominent product used in connection with filters for controlling or limiting the short-wave ultraviolet radiation emitted by artificial sources. The ultraviolet transmission of this glass varies somewhat from batch to batch as is characteristic of a product in which minute quantities of impurity and perhaps process-factors are so influential.

Corex A is very transparent to radiant energy as short as λ2500. According to Coblentz a specimen of Corex A solarized, as indicated in Fig. 37, upon exposure to a quartz mercury arc at a distance of 10 cm.

A piece of this glass after exposure for 14 months in a green-house roof was found to have the same transmission in the ultraviolet as a new specimen. After grinding and polishing it was found to transmit 89 per cent at λ3024. Doubtless, its constancy of ultraviolet transmission or failure to solarize under exposure to sunlight is due to the fact that it absorbs very little ultraviolet energy in sunlight. The short-wave limit of

sunlight is practically at λ2950 and this glass transmitted 91 per cent throughout the ultraviolet spectrum of sunlight. The reflection from the two surfaces of the polished specimen accounts for nearly all the remaining 9 per cent. Coblentz and Stair also obtained similar results with other specimens of Corex A exposed at higher altitudes for six weeks in Arizona. That is, sunlight appears to produce little or no change in this product. Naturally the fundamental law—only energy absorbed can bring about a reaction—explains these results.

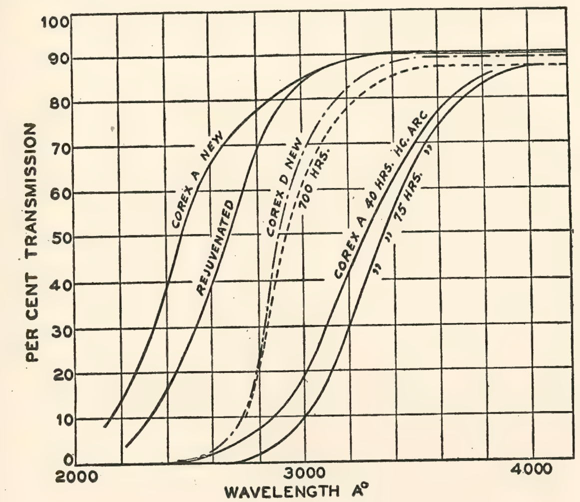

FIG. 37. Solarization of Corex glass. The curves with solid lines are for Corex A new and after exposure to radiation from a quartz mercury arc. The partial rejuvenation due to heating is also shown. The curves with broken lines are for new Corex D and after 700 hours' use as a bulb for the Sunlight (Type S-1) lamp.

The results with ultraviolet radiation from a quartz mercury arc are quite different. Although the transmission of new Corex A is unusually high for energy shorter than λ2600 it absorbs considerably between λ2000 and λ2900. This causes a great change in the ultraviolet transmission, as indicated in Fig. 37. According to Coblentz and Stair, Corex A acquires a reddish tint after exposure to the quartz mercury arc and, as is seen, it transmits eventually very little of the biologically-active radiation between λ2800 and λ3200. The reddish color is

more intense at the surface exposed and decreases with depth. Long exposure to a carbon arc, equipped with a glass globe which transmitted no energy shorter than λ3100, had no effect upon a new specimen. The solarized specimens are partially rejuvenated by heating.

The curves with broken lines in Fig. 37 are for a specimen of Corex D used as a bulb for the Sunlight (Type S-1) lamp when new and after being used for 700 hours. This new source of artificial sunlight consists of an intense mercury arc between tungsten electrodes and in parallel with a tungsten filament. This bulb of Corex D glass was subjected to intense ultraviolet radiation of short wavelength but very little change in ultraviolet transmission could be detected after 700 hours. The work of others verifies this. Corex D seems to be a fairly stable product and should find many uses in the new developments of artificial sunlight. Its short-wave limit is quite satisfactory and apparently it can be produced with considerable certainty. It is a good example of a fairly stable and efficient glass for transmitting the biologically-active radiation while absorbing energy of shorter wavelengths which are particularly harmful to the eyes. It is a worthy mark at which others may aim. It is seen that the problem of producing a satisfactory stable glass for transmitting the ultraviolet energy in sunlight is an easier one than that of producing a stable product for use with sources emitting considerable energy shorter than λ2900. However, owing to the seasonal failure of sunlight and to the general inadequacy of daylight indoors, as measured by biological effectiveness, the need for such a glass is limited. The production and utilization of artificial sunlight demand more and better glasses, particularly for illuminating glassware.

The temperature of a glass during its exposure to ultraviolet radiation should have some effect upon the result. We have explained the marked stability of Corex D under the severe conditions indicated in Fig. 37 as possibly due in part to the fact that the temperature of the glass is high enough to reverse the process of solarization almost completely. However, the glass appears stable enough without this partial explanation. Coblentz and Stair found that two glasses (Helioglas and Vitaglass), which they tested at 15 deg. C and also at 70 deg. C, solarized somewhat more at the higher than at the lower temperature. A temperature of 200 deg. C is sufficient to rejuvenate glasses; that is, to eliminate much of the effect of exposure to ultraviolet radiation which they absorb. The rate of recovery depends upon the temperature to which the glass is heated. The bulb of the Sunlight (Type S-1) lamp is subjected to intense short-wave ultraviolet radiation but it operates at a temperature considerably higher than that necessary to rejuvenate glasses. Possibly the acceptability of glassware for light-sources will be determined by the temperature of operation and a high temperature may be advantageous in some cases.

TABLE XIX

PER CENT TRANSMISSION AT λ3024 OF VARIOUS GLASSES BEFORE AND AFTER PHOTOCHEMICAL STABILIZATION BY EXPOSURE OF 10 HOURS TO QUARTZ MERCURY ARC AT A DISTANCE OF 15 CM.

	Number of samples	Average Thickness in mm.	Per cent Transmission New	Per cent Transmission Stabilized
Fused quartz	1	4.7	92	92
Corex D	15	2.3	61	59
Neuglas	12	2.3	63	49
Uviol-Jena	14	2.3	58	43
Helioglas (Vioray) [1]	24	2.3	58	40
Sunlit	9	2.3	65	29
Vitaglass	19	2.3	48	23
Celoglass [2]	5	0.1	30	..
Quartzlite	16	1.9	0.5	0.5
Window-glass	14	3.3	0	0

[1] Foreign name for Helioglas.
[2] Wire mesh in cellulose acetate.

Although in Table XVII some data are presented for certain representative specimens in regard to solarization, Table XIX is a summary by Coblentz and Stair of the average of many specimens after apparently complete photochemical seasoning by means of a quartz mercury arc. These data apply to specimens which they examined prior to Feb. 1, 1929. Perhaps some improvements in these products have been made since then. The wavelength λ3024 is chosen because it is in the

region of biological effectiveness and apparently is spectrally near the maximum of erythemal and antirachitic effectiveness. Corex D and Neuglas are nearly equally efficient at λ3024 when new but the former is more nearly stable when new than the latter. Corex D does not lose its efficiency appreciably when exposed to the quartz mercury arc which verifies our results shown in Fig. 37.

After complete solarization or photochemical seasoning the transmission of these glasses becomes stabilized and remains constant unless subjected to heat-treatment. The systematic work of Coblentz and his colleagues reveals much improvement in some commercial glasses. Some of the newest glasses exhibit a higher transmission of the biologically-active radiation after solarization than earlier commercial products did before solarization. Of course, in practice the transmission after complete photochemical stabilization under conditions of usage is important. The minimum transmission which is practicable is a biological question first and then becomes an economic one. Eventually, a minimum requirement can be established for window-glass. It is not likely that such a minimum can be established in general for artificial sources differing widely in spectral character. Any equipment to be used for health-maintenance must deliver sufficient biologically-active energy over the period of exposure to justify its use. However, there is the question of duration of exposure and intensity of illumination. In dual-purpose lighting the footcandle will, doubtless, continue to be the measure of intensity and the intensity of the vital radiation must be in terms of footcandles with proper qualifications.

Fused quartz may be considered permanent when exposed to solar radiation. Although quartz mercury arcs seem to depreciate somewhat in their emission of radiant energy from λ1850 to λ2200, we do not find that the transmission of the quartz depreciates appreciably. We have examined specimens of fused quartz after thousands of hours use in mercury arcs and find that the quartz, after being cleaned, exhibits practically the same spectral range of transmission as new quartz. From well-exposed spectrograms of the radiation from an iron arc and a quartz mercury arc through the quartz specimens we determine the minimum wavelength transmitted. The results are summarized in Table XX. Although the specimens were not examined when new and they were made at different times in the regular course of manufacture, the permanency of the fused quartz is well emphasized. Although the dark deposit on the inner wall of the tubes decreases the output of short-wave energy, the quartz itself appears to remain practically unchanged.

TABLE XX

The Shortest Wavelengths of Radiation Transmitted by Specimens of Fused Quartz After Various Periods of Operation as Envelopes of the Quartz Mercury Arc

Hours in Use	Before Cleaning	After Cleaning
0	1973	1849
450	1973	1849
1000	2002	1849
6000	2225	1849
10000	1988	1849

Determinations of the short-wave limit of transmission are not generally an adequate basis for conclusions pertaining to the permanency of transmitting media. Combined with knowledge of the spectral-transmission characteristic of a substance the limiting values are of some use. In the case of quartz its spectral characteristic is known very well. Other glasses must be studied more in detail and the efficiency of transmission between λ2800 and λ3200 should be determined before and after stabilization. The limitations of merely determining the short-wave cutoff are illustrated by referring to Fig. 36. It is seen that this specimen of Vitaglass depreciated considerably in transmission in the range from λ2800 to λ3200. However, the shortest wavelength transmitted does not necessarily change in proportion. For example, well-exposed spectrograms of the radiation from a quartz mercury arc after various periods of exposure of the Vitaglass to it have limits as follows:

	New	After 10 hours	After 40 hours
Vitaglass, 2.28 mm.	λ2482	λ2537	λ2654
Corex D, 3.37 mm.	2220	2345	2482
Q-3, 2.27 mm.	2378	2482	2482

The short-wave limit of Corex D of 3.37 mm. thickness seems to change as much as that of the Vitaglass but actually the former is practically constant in its transmission of biologically-active radiation and the Vitaglass specimen depreciates considerably. The Q-3 is one of the glasses developed by us in co-operation with Clark and Spencer and following the procedure discussed in the preceding chapter. Another difficulty in drawing conclusions from limiting wavelengths upon spectrograms is the influence of exposure. Well-exposed spectrograms reduce this difficulty and comparisons should be made between spectrograms of equal exposure. Over-exposure may reveal spectral lines of still shorter wavelength. In fact, this emphasizes the value of experience in photospectrography. There are pitfalls in dealing with line spectra but they can be mastered only by experience. The interpretation of the short-wave end of continuous spectra is still more difficult owing to scattered light. This can be reduced by various means including proper filters, but without experience scattered light is usually unrecognized.

The permanency of reflecting media assumes a new importance when short-wave radiation must be controlled and conserved. The relatively few efficient metals and finishes such as chromium, aluminum, and aluminum oxide should not deteriorate appreciably due to exposure to ultraviolet radiation. However, some paints are likely to depreciate considerably. According to Stutz [17] the absorption of ultraviolet radiation by dry linseed oil and dry nitrocellulose lacquer results in brittleness and crumbling. He found that a lacquer film deteriorates in this manner more rapidly than the linseed oil. If a pigment which will reflect such radiation is incorporated in the oil or lacquer so that the destructive energy cannot penetrate into the body of the film, the latter will be protected more or less. If

the ultraviolet radiation accelerates a harmful reaction between the vehicle and the pigment, the surface may be destroyed. This surface crumbles and another layer is exposed to destructive action.

Stutz [17] studied the spectral transmission of many thin layers of pigment with the foregoing objective in mind. However, the data will also be useful in future development of paints for controlling ultraviolet radiation. His studies included the spectral range from λ3024 to λ4356. In order that zinc oxide may be completely opaque to radiant energy shorter than λ3700 it must be 0.00092 mm. thick or approximately three pigment particles in thickness. Carbon-black need be only two-thirds as thick. Lithopone must be ten times as thick or about 0.01 mm. and white lead nearly thirty times as thick or 0.027 mm. The average three-coat paint film is approximately 0.12 mm. and contains pigment aggregating about 0.04 mm. in thickness. A measure of the amount of radiation reflected from the pigment, together with the amount transmitted by the same thickness, indicates whether the pigment is opaque due to absorption or to reflection, or both.

As seen in Figs. 13-15, zinc oxide owes its opacity to radiation shorter than λ3700 largely to its absorption of this energy. Basic carbonate white lead reflects quite well between λ3700 and λ2800 and, therefore, owes much of its opacity to reflection. Titanium pigment owes its opacity in this spectral region to both reflection and absorption. Stutz has presented data pertaining to the transmission of ultraviolet radiation by thin films of 26 white pigments and about 40 colored pigments. Just as the demand for ultraviolet radiation stimulated the development of transmitting glasses it will encourage the development of enamels for lighting equipment and paints for the finish of interiors.

The permanency of colored materials is of interest commercially and sources of ultraviolet radiation have been in use for years in forced-testing of materials. Furthermore, with ultraviolet radiation as an accompaniment of light in dual-purpose lighting, the question arises as to the permanency of

wall finishes, furnishings, and other colored materials. With the increase in intensity of artificial lighting in show-windows the question of fading of materials became of considerable interest several years ago. Therefore, in 1925, we studied the entire question of fading.[29] We exposed representative colored materials under glass and also under a variety of glasses differing considerably in short-wave limit of transparency. The influences of air, moisture, and temperature were also investigated.

Inasmuch as most materials are exposed to sunlight and skylight after passing through glass a series of dyed ribbons purchased in the market were exposed to sunlight, skylight and to the radiation from tungsten-filament lamps used in lighting. Harrison and Sturrock in a survey of show-windows in Cleveland stores found the average daylight illumination of the display to be 235 footcandles. A summary of our tests of materials exposed under glass to sunlight, skylight and the radiation from tungsten-filament lamps showed the following exposures to cause approximately equal amounts of fading:

Gas-filled tungsten lamps	500 footcandle-hours
Skylight at northeast window	180 footcandle-hours
Sunlight and skylight at southwest windows	430 footcandle-hours

Apparently, for a given period of exposure skylight is nearly three times more productive of fading in dyed fabrics than the light from tungsten-filament lamps as measured in footcandles. Expressed in another way we found the following exposures produced approximately the same amount of fading:

Tungsten-filament lamps	100 footcandles for 500 hours
Skylight (northeast)	450 footcandles for 40 hours
Sunlight and skylight (southwest)	3900 footcandles for 11 hours

The foregoing daylight intensities of illumination are average values on a horizontal surface inside the window on bright days in the spring and fall. From these values it is seen that fabrics in general, whose colors are too fugitive to withstand high intensities of artificial lighting from tungsten lamps over

several weeks, could not be worn outdoors or be exposed to sunlight indoors a few hours without perceptibly fading.

We investigated the reciprocity law over a range of intensities from 50 to 2700 footcandles obtained from tungsten-filament lamps and found it to hold. That is, the degree of fading is proportional to the product of time (hours) and intensity of illumination (footcandles).

The quartz mercury arc and the white flame carbon arc are commonly used to accelerate fading in testing the permanency of materials. The mercury arc emitting large quantities of short-wave ultraviolet causes fading much more rapidly than sunlight. No comparisons were made with the quartz mercury arc because it is not used in general lighting. However, we found that the white flame arc required only about three-fourths as much time as the gas-filled tungsten lamp to produce the same degree of fading through glass. Both arcs seem to cause fading somewhat different in character from that of daylight.

With the advent of the Sunlight (Type S-1) lamp as a primary factor in dual-purpose lighting it became of interest to ascertain its effect upon the permanency of colored fabrics. It was possible to experiment with the same ribbons used in 1925 on which the fading records were preserved. The following are the conditions required for equal degrees of fading. The materials were exposed under glass excepting in the case of the Type S-1 lamp.

	Footcandles	Exposure
Tungsten lamps	50	2600 hours
Tungsten lamps	500	240 hours
Light from clear sky	In northeast window	18 days
Sunlight plus skylight	In southwest window	5 days
G. E. Sunlight (Type S-1) lamp	500 (no glass)	70 hours
White flame arc	500	75 hours

The daylight exposures were made from dawn to dusk on clear summer days, those exposed in the southwest window receiving direct sunlight for 5 or 6 hours per day. The short-wave limit of the radiation emitted by the Sunlight (Type S-1)

lamp is λ2800. The white flame arc emits some radiation shorter than this wavelength. However, the foregoing tests were made on commercial colored ribbons, of a wide range in color, exposed under ordinary glass. Therefore, no radiant energy shorter than λ3100 reached the fabrics.

Owing to the fact that ultraviolet radiation from artificial sources and the short-wave radiation in sunlight are photochemically active, it is of interest to ascertain the influence of such radiations upon fading. Sets of ribbons were covered with strips of glass having different short-wave limits of transmission and exposed to direct sunlight plus some skylight. The first was a strip of fused quartz whose short-wave limit (λ1900) was far outside the spectral limits of the illuminants used. The next strip was thin Pyrex having a short-wave limit at λ2850. The other strips were specially selected clear and colored glasses having fairly sharp cutoffs and short-wave limits, respectively, at λ3130, 3650, 4350, 4800, 5570 and 5770.

Most of the colored ribbons showed progressively less fading from the quartz strip to the red filter with cutoff at λ5770. For these the reduction of fading between steps was possibly more than might be expected on account of the reduction in total radiant energy transmitted by the successive glasses although no attempt was made to evaluate the amount of energy transmitted. However, one third of the ribbons showed a marked difference in the amount of fading under the two glasses with short-wave limits of transmission at λ5570 and λ5770, respectively. This indicated that the yellow-green and yellow rays caused more fading in some dyes than the entire solar energy longer than λ5770. Although this test with a series of filters of various short-wave cutoffs did not reveal any marked fading power for any spectral range of sunlight, it has been seen that skylight faded materials three times as rapidly as the radiation from tungsten lamps. This indicates that the long-wave ultraviolet or short-wave visible radiations or both are more effective in producing fading than the radiation between this region and λ5770.

It has long been recognized that energy must be absorbed

in order to be effective in fading colored materials. Therefore, for example, a red fabric might be expected to fade more rapidly under solar radiation than under the radiation from tungsten lamps because the former contains a relatively greater proportion of short-wave radiation (absorbed by the red fabric) than the latter. However, the absorption of energy of a particular wavelength does not necessarily result in fading; it may be altered into heat energy instead of causing or entering into a chemical reaction. Therefore, the color of a material may not give any indication of the color of light or wavelength of radiation which will cause the greatest amount of fading. In fact, our results do not exhibit any conspicuous relationship between the color of the light absorbed and the amount of fading produced. The absorption spectrum of a colored material cannot do more than to indicate where the energy causing fading may be looked for. The permanency of any dye or pigment appears to be an individual matter and no generalization may be made excepting possibly that short-wave utraviolet, shorter than λ3000, is particularly active in altering materials subject to photochemical reaction.

It appears that dyed materials can scarcely be faded at all by exposure to 50 footcandles from tungsten-filament lamps for periods up to 200 hours or more. About one-half the materials showed some slight fading under

120 hours' exposure to 500 footcandles from tungsten lamps.
25 hours in direct sunlight (southwest window).
40 hours in skylight (northeast window).
35 hours' exposure to 500 footcandles from Sunlight (Type S-1) lamps.

Of the colored materials exposed to 5 footcandles from tungsten lamps for 1600 hours at room temperature only one-third of them showed any fading and these were just perceptibly faded.

All materials showed some fading in solar radiation longer than λ5570 if of sufficient intensity and duration. However, the fading was greatly reduced or practically negligible for some of the materials, even for excessive exposures, when all the radiant energy shorter than λ5770 was screened off.

Although a given degree of fading is produced by a lesser exposure (footcandle-hours) from daylight than from tungsten lamps, this does not mean that long-wave ultraviolet radiation and short-wave visible radiation possess sufficiently greater fading power than the energy in the middle of the visible spectrum to account for all the difference. The colored materials represented the entire gamut of colors and the law of averages should account for more fading in general by an illuminant containing more or less equal amounts of energy of all wavelengths. Sunlight and skylight qualify in this respect much better than the radiation from tungsten lamps and this may account for some of the difference. However, the combination of direct sunlight and the skylight entering a window did not cause much more fading than the same footcandle-hours with tungsten lamps. Therefore, the excess of long-wave ultraviolet and short-wave visible radiation in skylight must be particularly active.

Enclosing the colored materials in a vacuum practically inhibited fading with about one-half the materials tested and greatly reduced the fading of others.

Temperature had very little effect upon the rate of fading in the range from 85 to 120 deg. F, but at 150 deg. F the fading appreciably increased.

The effect of moisture was tested by circulating moist air through glass tubes containing the colored materials while they were exposed to the radiant energy. It was concluded that moist air did not have a very appreciable effect upon the rate of fading under the conditions of these researches.

Some of our conclusions were later confirmed by an extensive investigation conducted by the American Association of Textile Chemists and Colorists.[30]

CHAPTER X

Incandescent Solids

Measurements of biologically-active radiation and effects must eventually form the foundation for the production and utilization of artificial sunlight. These data are accumulating satisfactorily notwithstanding the experimental difficulties involved in obtaining them. In the case of incandescent solids which radiate energy similar in spectral distribution of energy to that of the theoretical black-body, computations may be depended upon to provide a view of the possibilities. Much study has already been given to the applicability of laws of radiation to such incandescent solids so that the results of computations are sufficiently dependable for the present purpose. The spectral sensitivities of various biological processes are not thoroughly established. Therefore, certain spectral limits must be chosen in order to present a co-ordinated view of the relationships of such factors as footcandles, lumens per watt and intensity of radiant power (or energy) of certain spectral ranges, to the temperature of the solid radiator.

Color-temperature is a convenient value to use in this connection. An incandescent solid which at a certain known or unknown temperature emits light of the same color as that emitted by the theoretical black-body at a known temperature is said to have a color-temperature equal to the temperature of the so-called black-body. This also means that the spectral distribution of the energy emitted by the incandescent solid throughout the visible spectrum at a given color-temperature is practically the same as that of the black-body radiator at its actual temperature.

The radiation laws are adequately discussed in advanced

treatises of physics; therefore, only a few steps are introduced herewith. Planck's equation

$$E_\lambda = \frac{C_1}{\lambda^5 e^{c_2/\lambda T} - 1} \qquad (1)$$

represents the energy or radiant power emitted per unit area of the radiating surface for any wavelength λ by a black-body at an absolute temperature T (degrees Kelvin = degrees Centigrade plus 273). In the equation, C_1, C_2 and e are constants. For example, the spectral distribution of energy emitted by a black-body at 6000 deg. K in Fig. 27 may be computed for each wavelength by using the proper values of these constants. In making the computations for such a case the only variable on the right-hand side of the equation is λ or wavelength.

The total energy emitted per second per unit of area of a black-body radiator is proportional to the fourth power of the temperature. This fundamental law is expressed as follows:

$$E = \sigma T^4 \qquad (2)$$

where σ is the Stefan-Boltzmann constant having a value of 5.709×10^{-12} (watts per sq. cm. per deg.$^{-4}$). The total energy is readily computed for a black-body radiator of known area at any temperature T (deg. K). The area under the curve (Fig. 27) representing the spectral distribution of energy from a black-body at 6000 deg. K, is proportional to the total energy emitted. If two vertical lines are erected at two different wavelengths, the ratio of the area between them to the total area is the fraction of the total energy emitted in this spectral range. The values of relative energy are converted into absolute values by specifying the area of the source or any suitable absolute factor.

Another important fundamental relationship is

$$\lambda_m T = A \qquad (3)$$

known as Wein's displacement law. The spectral distribution of energy emitted by a black-body radiator always has a maximum, λ_m. The product of this value and the temperature in deg. K is equal to a constant, A, whose value is 2890 when the wavelength is expressed in microns and equals 2890×10^4 when λ_m is expressed in Angström units. It is evident that as the temperature decreases the wavelength of maximum emission of energy recedes toward longer wavelengths. This is illustrated in Fig. 27 by the various energy-distribution curves. Only one is that of a black-body, 6000 deg. K, but the others are equivalent, respectively, to black-bodies of lower temperatures. Incidentally, the areas under all the curves in Fig. 27 are equal, which means equal total energy emitted by the respective incandescent radiators. It is also evident that the color of the total light becomes more yellow as the temperature decreases or as the wavelength of maximum energy increases. This is due to the fact that with decrease in temperature the short-wave visible radiation decreases more rapidly than the yellow, orange, and red rays. Conversely, the color becomes less and less yellow as the temperature increases. It becomes white at a color-temperature of 5600 deg. K (Fig. 7, Table III). With further increases in temperature the total light becomes more and more bluish.

In order to apply the theoretical black-body radiation laws to other solid radiators certain factors must be taken into account. In the first place the color-temperature T_c must be used instead of the true temperature of the non-black radiator. For incandescent tungsten the color-temperatures corresponding to true temperatures are presented in Table XXI. Besides this the emissivity of the tungsten must be known for the various spectral regions. The emissivity of a black-body is always unity, but for non-black bodies it is always less.

When an incandescent solid (non-black) is at a temperature T the temperature of a black-body radiator with which it is compared must be at a temperature T_c in order that the light be of the same color as that of the former. Then the non-black solid is said to have a color-temperature T_c. At these temperatures the spectral intensities of energy emitted by the non-black radiator at two wavelengths bear a definite ratio to the

intensities from a black-body at the same wavelengths. This ratio is called the color-emissivity of the non-black incandescent solid.

The total energy radiated per second per unit area by the non-black radiator at temperature T is a fraction of the energy radiated per second per unit area by a black-body at the same temperature. This fraction is the total emissivity of the non-black solid. These values for tungsten, presented in Table XXI, are seen to vary with temperature and also vary some-

TABLE XXI

DATA DETERMINED BY FORSYTHE AND WORTHING [32] FOR TUNGSTEN IN A VACUUM WITHOUT ANY CONDUCTION OR CONVECTION LOSSES

Temperature deg. K		Emissivity		Lumens per watt	
True	Color	Color	Total	Tungsten at temp. T.	Black-body at temp. T_c
1500	1517	0.383	0.192	0.20	
1800	1825	.376	.236	1.16	
2000	2033	.370	.260	2.78	0.67
2200	2242	.364	.279	5.47	1.75
2400	2452	.359	.296	9.37	3.67
2600	2663	.353	.311	14.28	6.70
2800	2878	.347	.323	20.43	10.8
3000	3094	.343	.334	27.1	16.0
3200	3311	.338	.341	34.6	22.1
3300	3422	.335	.344	38.5	28.9
3400	3533	.332	.348	42.6	
3500	3646	.329	.351	45.9	
3655	3817	.324	.354	53.1	

what in different spectral regions. In all our computations, corrections have been made in accordance with the values most recently determined by Forsythe and Worthing.[32] The necessary data are available at least down to λ3400 and there is sufficient evidence to make computations throughout the ultraviolet region satisfactory for the present purpose.

The spectrograms reproduced in Plate III show that biologically-active radiation is emitted by tungsten filaments. These were made carefully through filters which transmitted only ultraviolet radiation so that scattered light was practically

eliminated. The bulbs were of 888 glass and Corex D. The shortening of the spectrum due to interposing common window-glass is definitely shown. The effect of duration of exposure is demonstrated by these spectograms.

The color-temperatures of the older filament-lamps using carbon in various forms, and also osmium and tantalum, varied from 2000 to 2400 deg. K. The modern tungsten-filament lamps are improved from time to time so that data are subject

TABLE XXII

LUMINOUS EFFICIENCY, MAXIMUM TEMPERATURE (DEG. K), COLOR-TEMPERATURE T_c OF TUNGSTEN-FILAMENT LAMPS AS DETERMINED BY FORSYTHE AND WORTHING [32]

	Lumens per watt	Temperature (deg. K)	
		Maximum	Color
(Vacuum)			
10-watt	8.0	....	2410
25	9.8	....	2450
40	10.0	....	2460
(Gas-filled)			
50-watt	10.0	2685	2670
75	11.8	2735	2705
100	12.9	2760	2740
200	15.2	2840	2810
300	16.3	2870	2840
500	18.1	2930	2920
1000	20.0	2990	2980
2000	21.2	3020	3000
(Special)			
1000-watt stereopticon	24.2	3185	3175
900-watt movie	27.3	3290	3220
10-kilowatt	31.0	3350	3300
30-kilowatt	31.0	3350	3300

to change. However, the latest data presented in Table XXII are satisfactory for our present purpose. The luminous efficiency (lumens per watt) increases rapidly as the temperature increases. Likewise, as is evident later, the output of ultraviolet radiation rapidly increases so that apparently the tungsten filament operating at high temperatures is not without promise as a source of radiation of mild biological value.

Although the method of computing the amount of radia-

tion emitted by incandescent solids has been briefly sketched, the computations have been tedious and time-consuming. Owing to the need for short-cuts, Holladay,[33] a colleague, has developed formulas and tables which greatly reduce the labor involved. The proportion of spectral energy emitted from a black-body radiator at a given temperature between two wavelengths may be computed very quickly. Similarly, non-black radiators are treated without the usual labor. Using his

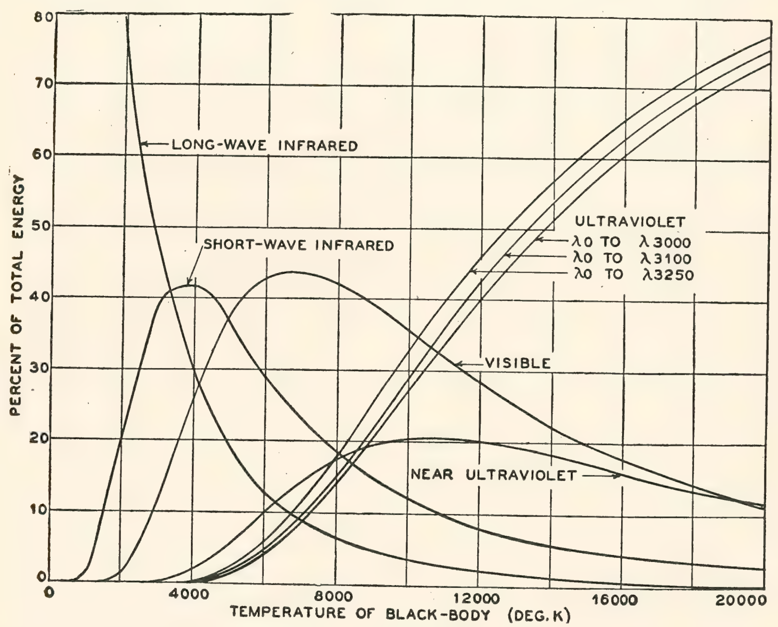

Fig. 38. Showing the influence of temperature upon the percentages of total radiation emitted by a black-body radiator in various spectral regions.

short-cut method, Holladay computed the spectral-energy data in the charts and tables presented in this chapter.

Although black-bodies exist only theoretically, they are the basis of all considerations of incandescent solid radiators. Furthermore, there are substances such as carbon which closely approach them and even the metals exhibit black-body characteristics when emissivity is taken into account. Therefore, a general view of radiation emitted in various spectral ranges, as influenced by temperature, is best introduced by data per-

taining to black-bodies. In Fig. 38 the percentages of total energy emitted in certain spectral regions are shown for a wide range of temperatures of a black-body radiator. The higher temperatures are unattainable at present by solids but there is no reason to believe that the practical limit will long remain at 3655 deg. K, the melting-point of tungsten. Carbon melts at a much higher temperature and certain alloys are not without promise. It is seen that the near ultraviolet (λ3000

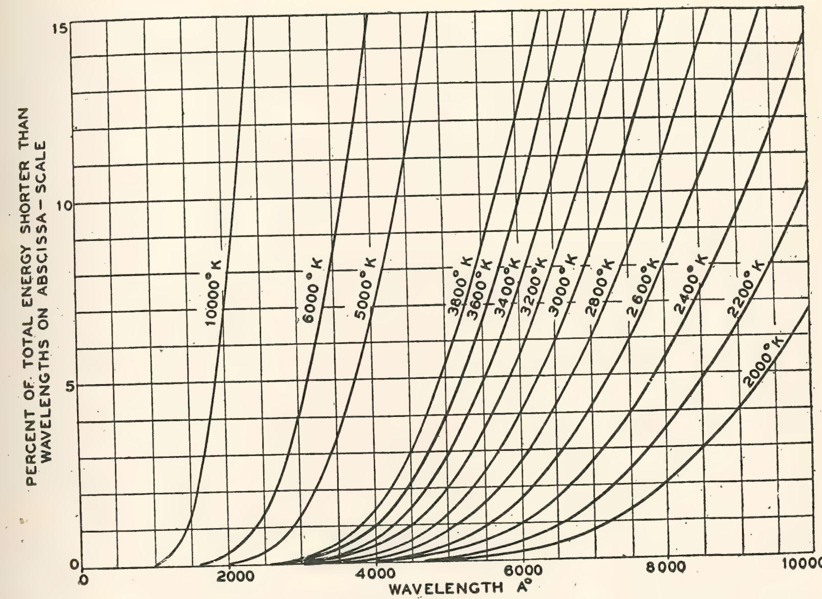

Fig. 39. The percentage of total energy emitted by a black-body shorter than any chosen wavelength on the abscissa-scale may be read from the curve representing the temperature of the radiator.

to λ4000), the visible and the short-wave infrared (λ7600 to λ14000) exhibit maximum percentages of the total radiation in the temperature range covered in Fig. 38. The biologically-active ultraviolet radiation continues to increase in percentage of total energy beyond this range of temperature. These data are presented in Table XXIII. The total energy at each temperature is unity and the fractions for seven spectral ranges are presented. The sum of five of the fractions equals unity.

In Fig. 39 the percentage of total energy shorter than any wavelength on the abscissa-scale emitted by a black-body at a given temperature may be read from the curve corresponding to this temperature. For example, 6.7 per cent of the total energy emitted by a black-body at 5000 deg. K is shorter than λ4000. About 4 per cent of the total energy emitted by a black-body at 6000 deg. K is shorter than λ3000 and 1.4 per cent is shorter than λ2500. Therefore, 2.6 per cent of the total energy is radiated between λ2500 and λ3000. A plot of

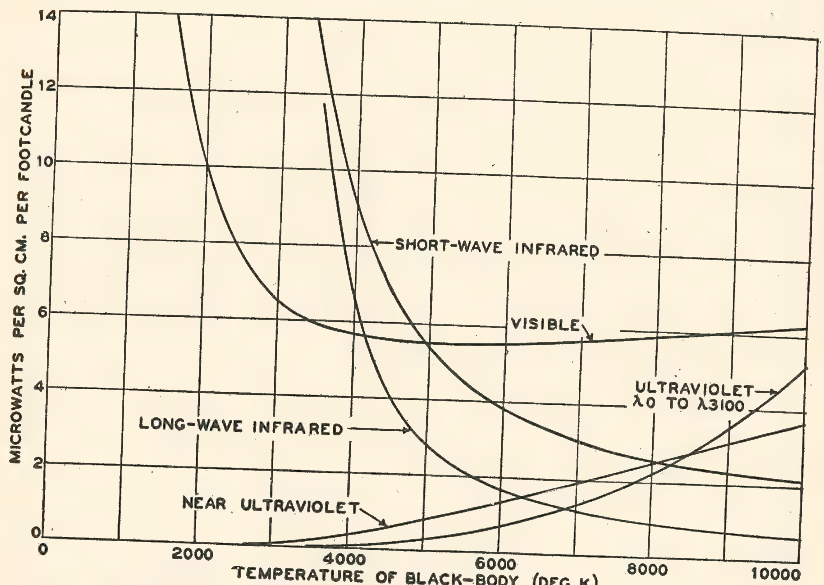

FIG. 40. Indicating the influence of temperature of a black-body upon the radiant power received per sq. cm. per footcandle of illumination.

temperature and per cent of total energy emitted in any chosen spectral range may be readily constructed from Fig. 39. These data are included in Table XXIII.

The influence of temperature of the black-body upon the amount of radiant power (microwatts per sq. cm.) per footcandle of illumination is shown in Fig. 40. It is seen that the visible radiation in microwatts per sq. cm. per footcandle remains fairly constant over a range of temperatures of the black-body radiator from 3500 to 9000 deg. K. The biologi-

cally-active radiation (shorter than λ3100) increases steadily. The temperatures represented by much of this scale are unattainable with solid radiators at the present time, but the range is interesting in presenting a full view. These data are presented in Table XXIV for various spectral regions throughout a wide range of temperatures. In the second column are the values of luminous efficiency (lumens per watt). In the last

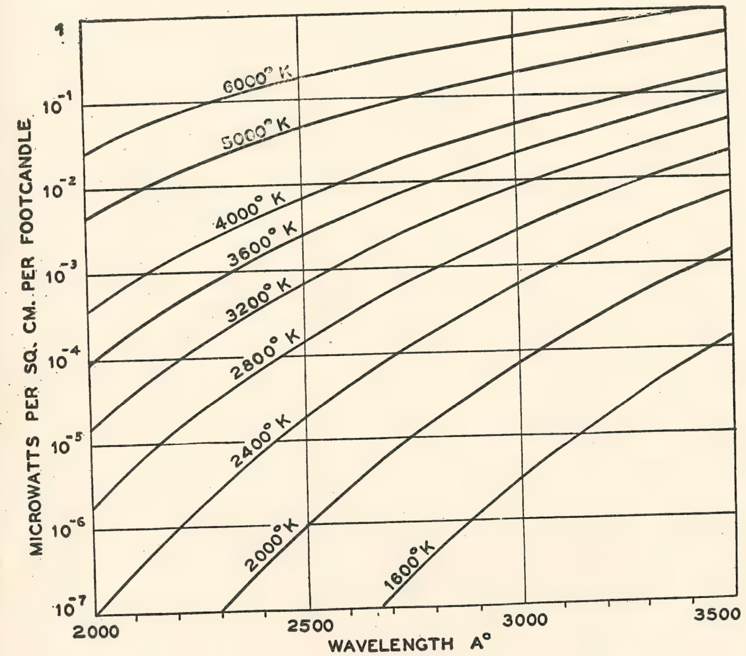

FIG. 41. The radiant power emitted by a black-body shorter than any chosen wavelength on the abscissa-scale may be read from the curve representing the temperature of the radiator. The ordinate scale is logarithmic.

column is given the total radiation which, of course, is the sum of the radiant power in the various spectral regions. The values in the last column of Table XXIV are smaller than the sum of values in columns 3 to 7 inclusive because the spectral ranges in the third and fourth columns overlap slightly. In the third column λ3100 is taken as the long-wave limit on account of biological value.

From Fig. 41 the microwatts of radiation (shorter than

any given wavelength in the abscissa-scale) which are received upon a sq. cm. under an illumination of one footcandle are obtainable for black-bodies varying in temperature from 1600 to 6000 deg. K. In order to encompass a large range on this

TABLE XXIII

FRACTION OF TOTAL RADIANT POWER EMITTED IN DIFFERENT SPECTRAL REGIONS BY A BLACK-BODY AT VARIOUS TEMPERATURES
(TOTAL RADIANT POWER IN EACH CASE EQUALS UNITY)

Temperature	Ultraviolet		Visible	Infrared	
Deg. K	λ0 to λ3100	λ3000 to λ4000	λ4000 to λ7600	λ7600 to λ14000	λ14000 to λInfinity
1200	......	4.83×10^{-10}	0.000108	0.0270	0.9729
1500	1.93×10^{-10}	9.9×10^{-8}	.00115	.0828	.916
1800	2.2×10^{-8}	3.0×10^{-6}	.00668	.1605	.8328
2000	1.95×10^{-7}	1.71×10^{-5}	.0143	.2152	.7704
2200	1.23×10^{-6}	6.7×10^{-5}	.0262	.2668	.707
2400	5.02×10^{-6}	2.0×10^{-4}	.0428	.313	.644
2500	1.06×10^{-5}	.00032	.0525	.332	.6152
2600	1.92×10^{-5}	.00051	.0632	.3499	.5864
2700	3.35×10^{-5}	.00076	.0741	.3655	.5586
2800	5.61×10^{-5}	.00109	.0883	.3786	.5320
2900	9.05×10^{-5}	.00153	.1013	.3905	.5067
3000	.000138	.00210	.1152	.4004	.4822
3100	.000208	.00281	.1297	.4083	.4592
3200	.000303	.00369	.1440	.4157	.4364
3300	.000432	.00472	.1595	.4192	.4162
3500	.000814	.0074	.190	.4242	.3778
3600	.00109	.00904	.2053	.4249	.3600
3800	.00185	.0130	.2352	.4229	.3275
4000	.00295	.01788	.2639	.4185	.2975
5000	.01636	.0545	.3777	.3639	.1908
6000	.04743	.1017	.4333	.2971	.128
7000	.0966	.1456	.4436	.2373	.0895
8000	.1586	.1784	.4260	.1891	.0649
10000	.2976	.2077	.3574	.1232	.0367
12000	.4296	.2037	.2849	.0831	.0228
15000	.5880	.1731	.1989	.0497	.0123
20000	.7549	.1180	.1132	.0246	.0050

small diagram, the scale of ordinates is logarithmic. To illustrate the use of the diagram let us take a temperature of 3200 deg. K for a black-body. The radiant power shorter than λ3100 received by a sq. cm. under an illumination of one foot-

candle is slightly more than 0.01 microwatts. For 100 footcandles this would equal about one microwatt. As already stated, these data for black-bodies are presented as a foundation. In order to transform the data from Fig. 41 into data pertaining to tungsten filaments it is necessary to multiply the

TABLE XXIV

MICROWATTS PER SQUARE CENTIMETER PER FOOTCANDLE OF ILLUMINATION RADIATED IN CERTAIN SPECTRAL REGIONS BY A BLACK-BODY AT VARIOUS TEMPERATURES

Temperature	Lumens Per Watt	Ultraviolet		Visible	Infrared		Total Radiation
Deg. K		λ0 to λ3100	λ3000 to λ4000	λ4000 to λ7600	λ7600 to λ14000	λ14000 to λInfinity	
1200	0.00374	......	.00014	31.0	7760.	280200.	288000.
1500	.0843	.000024	.0013	14.7	1052.	11700.	12770.
1800	.594	.00004	.0054	12.1	291.	1510.	1813.
2000	1.53	.00014	.0120	10.1	151.	541.	702.
2200	3.21	.0004	.0224	8.75	89.4	237.	335.
2400	5.81	.0009	.037	7.92	58.0	119.	185.
2500	7.45	.0015	.046	7.56	47.8	88.6	144.
2600	9.38	.0022	.059	7.30	40.2	67.4	115.
2800	13.95	.0043	.084	6.76	29.2	41.0	77.
3000	19.2	.0077	.117	6.45	22.4	27.0	56.
3100	21.9	.0102	.138	6.36	20.0	22.5	49.
3200	25.4	.0130	.157	6.12	17.7	18.4	42.4
3300	28.3	.0164	.180	6.06	15.9	15.8	38.
3500	34.4	.0255	.232	5.95	13.3	11.8	31.3
3600	37.7	.0310	.258	5.86	12.1	10.3	28.5
3800	43.8	.0454	.320	5.78	10.4	8.06	24.6
4000	50.1	.0634	.385	5.68	9.0	6.40	21.5
5000	73.9	.239	.795	5.52	5.3	2.79	14.6
6000	84.0	.607	1.30	5.54	3.8	1.64	12.8
7000	84.0	1.34	1.86	5.68	3.04	1.15	12.8
8000	78.2	2.17	2.45	5.84	2.59	.89	13.7
10000	61.3	5.21	3.64	6.26	2.15	.64	17.5

microwatts by a number varying from about 1.56 for a color-temperature of 2000 deg. K to 1.12 for a color-temperature of 3600 deg. K.

As already stated, the data pertaining to black-bodies are presented because of their fundamental interest. These data are valuable in completing the fundamental picture of radiation

from solid radiators throughout a wide range of temperatures. Similar data of definite practical interest are presented in Fig. 42 for tungsten-filament lamps just as they are now being made, excepting that the bulb is assumed to transmit radiation throughout the ultraviolet region without loss by absorption. The data have been computed for temperatures to the melting-point, some of which are beyond the highest yet employed in commercial tungsten-filament lamps. The various curves rep-

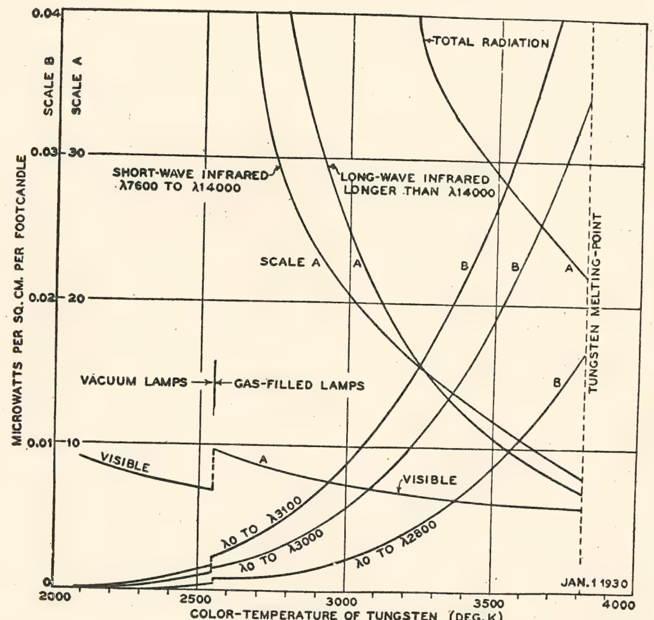

FIG. 42. Influence of color-temperature of tungsten filaments upon the radiant power in various spectral ranges received by each sq. cm. of surface per footcandle. The proper ordinate scale is indicated on each curve.

resent the relationship between color-temperature of tungsten and the radiation (microwatts per sq. cm.) per footcandle within certain spectral ranges. In order to present the entire view fairly well two scales, *A* and *B*, for the radiant power are employed and the curves are marked to indicate the scale to be used with it.

It is interesting to note the abrupt interruption in the course of the lower curves at the point where the vacuum lamps

TABLE XXV

FRACTION OF TOTAL RADIANT POWER EMITTED IN CERTAIN SPECTRAL REGIONS BY TUNGSTEN FILAMENTS AT VARIOUS TEMPERATURES

(THE TOTAL RADIATION FOR EACH TEMPERATURE IS EQUAL TO UNITY)

Color Temperature	Ultraviolet				Visible	Infrared	
Deg. K	λ2800 to λ3100	λ0 to λ3100	λ0 to λ3000	λ3000 to λ4000	λ4000 to λ7600	λ7600 to λ14000	λ14000 to λInfinity
1700	8.93×10^{-9}	9.65×10^{-9}	4.38×10^{-9}	.0000021	.0076	.132	.860
2065	4.90×10^{-7}	9.57×10^{-7}	2.06×10^{-7}	.000042	.0270	.230	.743
2160	10.2×10^{-7}	11.9×10^{-7}	6.92×10^{-7}	.000078	.0348	.254	.711
2195	1.44×10^{-6}	1.68×10^{-6}	0.91×10^{-6}	.000094	.0378	.262	.700
2400	6.12×10^{-6}	7.5×10^{-6}	4.32×10^{-6}	.000276	.0586	.307	.635
2460	9.1×10^{-6}	11.06×10^{-6}	6.44×10^{-6}	.000363	.0650	.319	.616
2670	2.93×10^{-5}	3.7×10^{-5}	2.25×10^{-5}	.000852	.0917	.353	.554
2740	4.13×10^{-5}	5.26×10^{-5}	3.27×10^{-5}	.00110	.101	.363	.535
2810	5.72×10^{-5}	7.42×10^{-5}	4.63×10^{-5}	.00141	.111	.371	.516
2920	8.9×10^{-5}	11.85×10^{-5}	7.7×10^{-5}	.00198	.127	.383	.488
2980	1.16×10^{-4}	1.54×10^{-4}	1.003×10^{-4}	.00239	.136	.388	.474
3220	2.75×10^{-4}	3.84×10^{-4}	2.58×10^{-4}	.00453	.172	.404	.419
3300	3.53×10^{-4}	5.01×10^{-4}	3.44×10^{-4}	.00548	.185	.406	.403
3500	6.23×10^{-4}	9.2×10^{-4}	6.5×10^{-4}	.00836	.215	.410	.366
3800	13.0×10^{-4}	20.3×10^{-4}	14.85×10^{-4}	.0143	.259	.409	.316

leave off and the gas-filled lamps begin. The point has steadily receded to lower and lower temperatures. At the present time the 40-watt gas-filled tungsten lamp is about to replace the vacuum lamp of the same wattage. It is seen that the short-wave ultraviolet rapidly increases with temperature of the filament. For example, the energy of maximum erythemal effectiveness per footcandle in the radiation from melting tungsten is about six times that from a tungsten filament at a color-temperature of 3000 deg. K. The visible radiation per footcandle decreases gradually with increase in temperature. The infrared and total radiation per footcandle, only partially shown in Fig. 42, decrease rapidly as the temperature increases.

In Table XXV are presented the fractions of the total energy (taken as unity) radiated in certain spectral ranges. An idea of the current size of tungsten lamp for a given color-temperature in Table XXV is readily obtained by referring to Table XXII. On comparing the luminous efficiencies in Table XXI with those in Tables XXII and XXVI it should be noted that the values in Table XXI are for tungsten in a vacuum and corrected to the condition of no conduction or convection losses. Such losses decrease the luminous efficiency of actual tungsten-filament lamps.

The data of most practical interest pertaining to tungsten-filament lamps are presented in Table XXVI from which Fig. 42 was plotted. Present tungsten lamps of the higher wattages operate at temperatures in the region from 3000 to 3400 deg. K. In the third column of this table the values of radiant power (microwatts per sq. cm.) per footcandle for the region λ2800 to λ3100 are presented. In the fourth column are the corresponding values for radiant power per footcandle of wavelengths shorter than λ3100.

Let us take the practical case of a tungsten-filament lamp operating at a color-temperature of 3220 deg. K. Each sq. cm. of a surface illuminated by this light-source (equipped with a bulb transmitting all the ultraviolet radiation) receives 0.0151 microwatts of radiation shorter than λ3100 for each footcandle or 1.51 microwatts for each 100 footcandles. Economic

TABLE XXVI

MICROWATTS PER SQUARE CENTIMETER PER FOOTCANDLE OF ILLUMINATION SUPPLIED IN CERTAIN SPECTRAL REGIONS BY TUNGSTEN FILAMENTS AT VARIOUS TEMPERATURES

Color Temperature	Lumens per watt	Ultraviolet				Visible	Infrared		Total Radiation
Deg. K		λ2800 to λ3100	λ0 to λ3100	λ0 to λ3000	λ3000 to λ4000	λ4000 to λ7600	λ7600 to λ14000	λ14000 to λInfinity	
(Vacuum tungsten-filament lamps)									
1700	.59	16.3×10^{-6}	17.6×10^{-6}	$8. \times 10^{-6}$	.0038	13.8	241.	1565.	1820
2065	3.	1.76×10^{-4}	$2. \times 10^{-4}$	1.07×10^{-4}	.0152	9.72	82.8	267.6	360
2160	4.4	2.5×10^{-4}	2.92×10^{-4}	1.70×10^{-4}	.0190	8.53	62.2	174.2	245
2195	5.	3.1×10^{-4}	3.61×10^{-4}	1.95×10^{-4}	.0202	8.13	56.4	150.5	215
2400	8.	8.26×10^{-4}	10.1×10^{-4}	5.83×10^{-4}	.0373	7.91	41.5	85.7	135
2460	10.	9.82×10^{-4}	$12. \times 10^{-4}$	6.96×10^{-4}	.0392	7.02	34.5	66.5	108
(Gas-filled tungsten-filament lamps)									
2670	10.0	.00317	.004	.00243	.092	9.90	38.2	59.8	108
2740	12.9	.00343	.00437	.00272	.091	8.38	30.1	44.4	83
2810	15.2	.00406	.00527	.00329	.100	7.90	26.3	36.6	71
2920	18.1	.00530	.00705	.00458	.118	7.56	22.8	29.0	59.5
2980	20.	.00624	.00829	.00540	.129	7.32	20.9	25.5	53.8
3220	27.3	.0108	.0151	.0107	.178	6.76	15.9	16.5	39.4
3300	31.	.0122	.0174	.0119	.190	6.42	14.1	14.0	34.7
3500	(37)	.0181	.0268	.0189	.243	6.26	11.93	10.65	29.1
3800	(48)	.0291	.0455	.0333	.320	5.80	9.16	7.09	22.4

intensities of illumination at the present time are certainly between 30 and 100 footcandles regardless of the lag in lighting practice. For the present purpose let us take 100 footcandles as justifiable in the work-world.

According to computations by Forsythe and Christison (Table VI), which are sufficiently verified by other considerations, the radiation shorter than λ3100 in midday sunlight equals 20 microwatts per sq. cm. for a clear day in midsummer in the latitude of Cleveland. Incidentally, the intensity of illumination was also computed to be 8540 footcandles, which is verified by many measurements made by us.

Assuming the reciprocity law to hold over this range, as our work has proved for erythema over quite a range, the tungsten lamp supplying 1.51 microwatts per sq. cm. per 100 footcandles would require 20/1.51 or 13 times as long to deliver the same amount of biologically-active radiation. According to our data (Tables VII to X), average untanned skin requires an exposure of 20 minutes to midday midsummer sunlight for the production of a minimum perceptible erythema. If the reciprocity law holds beyond the range for which we have tested it for erythema (including exposures as great as three hours), then an equivalent exposure to the tungsten lamp would be 13 times 20 minutes or about four hours. A minimum perceptible erythema would not be expected because the repair processes which are always at work would doubtless prevent it over such a long period. Erythema cannot result unless destruction of superficial skin-layers takes place more rapidly than the repair-work. Furthermore, erythema is not necessary in order to obtain biological benefit.

Computations indicate that the radiation shorter than λ3100 is only 6 microwatts per sq. cm. for noon sunlight in spring and fall. This is only one-third that in midday midsummer sunlight. An equivalent exposure to 100 footcandles supplied by the tungsten filament at a color-temperature of 3220 deg. K would need be only about one-third that required to compete with midday summer sunlight.

It is conceded that this effectiveness of the lesser intensities

of biologically-active radiation operating for a longer time, perhaps hours, cannot be settled entirely by computations, but much light can be thrown upon the subject in this manner. Besides, our studies of erythemal effectiveness as based upon footcandles, of the reciprocity law as applied to erythema, and actual biological experiments with tungsten filaments in special bulbs which we initiated several years ago, dovetail nicely into this entire picture. However, before discussing these let us consider a brief summary bearing in mind obvious cautions or qualifications in interpreting the data into the biological realm.

Besides intensity, it is necessary to consider exposure. Average untanned skin exposed 20 minutes to midday midsummer sunlight on a clear day in the latitude of Cleveland, O., develops a minimum perceptible erythema. The equivalent exposures during which the same total amount of radiation shorter than λ3100 would fall upon a sq. cm. of surface exposed to light from the tungsten filament (3220 deg. K) as falls upon the area in 20 minutes under midsummer sunlight, are as follows:

50	footcandles	for	520	minutes
100	footcandles	for	260	minutes
200	footcandles	for	135	minutes
500	footcandles	for	52	minutes
1000	footcandles	for	26	minutes

An intensity of illumination of 50 footcandles is already in use in the work-world. It is not difficult to show that 100 footcandles is economically possible in many places. The period of exposure under 100 footcandles as shown in the foregoing paragraph is 4.3 hours. Most of the work-world spends an average of nearly this much time under artificial light. When it is considered that the best sunlight has been used as a basis for the foregoing analysis it is seen that tungsten-filament sources are not without promise in dual-purpose lighting. Certainly with cloudiness, smoke, haze, and winter months of very feeble biologically-active radiation a sunlight equivalent is readily obtained from tungsten filaments at practicable intensities in footcandles and duration of exposures. Further-

more, the average indoor worker receives so little sunlight per day that it appears that tungsten filaments may readily improve upon these sunlight exposures at ordinary intensities.

It should also be borne in mind that preventative or prophylactic dosage is considerably smaller than curative dosage. A minimum perceptible erythema produced daily is well within the range of usual curative dosages. Therefore, the foregoing values of footcandles and hours' exposure can be reduced considerably for health-maintenance of healthy persons.

Only one case has been discussed herewith but from the illustrations and tabulated data a wide range of possibilities can be examined by anyone. From these data it is seen that any improvement in solid radiators which will enable them to be operated at higher temperatures increases their opportunity in dual-purpose lighting.

The final proof of the effectiveness of the radiation from tungsten filaments or other solids operating at high temperatures must come from biological researches. On the other hand they are of little value unless supported by physical data. Every science or art must be constructed upon physical science. Biological researches and particularly those in radiation-therapy have been sorely in need of physical measurements and methods. After certain knowledge is available physical analysis can readily predict the efficacy of radiation and the intensities and exposures necessary. Fortunately, we have sufficient data to enable us to make some predictions in regard to tungsten-filament sources.

With this view of the situation, several years ago we inaugurated some biological researches with tungsten filaments in special bulbs. In this work we have had the co-operation of various authorities. While planning this work we received some data from Profs. Dutcher and Honeywell (Penn State) which they published later.[34] A summary of the data is presented in Table XXVII. They experimented with two groups of rats fed upon a restricted diet for 3 and 5 weeks, respectively. They hung an ordinary 100-watt tungsten lamp over the cage and operated it 8 hours a day. They did not measure

the intensity of illumination but from their description it was of the order of 10 footcandles. Another cage was covered with muslin cloth through which some light filtered. Another group was kept in the ordinary light of the laboratory which was restricted chiefly to a low intensity of artificial light. The fourth group was kept in a light-tight box. It is seen that the percentage of bone-ash was greatest for the group which received the light from the 100-watt tungsten lamp with *ordinary glass bulb*.

We have supplied Dr. Maughan 60-watt tungsten-filament lamps in special ultraviolet-transmitting bulbs. He used them

TABLE XXVII

Ossification of Bones of Rats as Affected by Artificial Light. Age of Rats at Start of Test, 21 Days

Group No.		Bone Ash Per Cent
	21-day feeding period	
1	100-watt Mazda lamp, 8 hrs. per day	31.82
2	Dark cage, covered with muslin cloth	22.44
3	Laboratory light (mainly artificial)	25.33
4	Dark cage, covered with cardboard	16.65
	35-day feeding period	
5	100-watt Mazda lamp, 24 hrs. per day	50.59
6	Dark cage	18.46
7	Laboratory light	26.48
8	Two drops cod-liver oil daily	38.95

in brooders in such a manner that small chicks could get close to them. These chicks developed perfectly free from rickets without exposure to sunlight or without being fed any special antirachitic food.

A second experiment was conducted by Dutcher and Honeywell over a 5-week period. In this case about 10 footcandles from the 100-watt ordinary tungsten lamp was applied to one cage continuously. They also compared the efficacy of cod-liver oil. Here again, the 100-watt tungsten lamp showed a definite effect. The thin glass bulb of ordinary glass transmits a slight amount of energy at $\lambda 3000$ and a measurable amount at $\lambda 3100$. Whether or not it was this energy or the much

greater amount at λ3200 which was responsible for the result is not known. However, these results indicate a much lower threshold value of biologically-active radiation than has been generally recognized.

In experiments inaugurated several years ago we had the co-operation of Dr. Maughan (Cornell). Some results are summarized in Table XXVIII. The chickens were fed upon a restricted diet until they were suffering with severe rickets. One group was illuminated 5 hours per day to an intensity of approximately 20 footcandles by means of a tungsten filament in a special bulb. This bulb was made of a glass which

TABLE XXVIII

RESULTS WITH CHICKENS HAVING RICKETS

Group	
I	5M-1F 500-watt tungsten special bulb Exposure 5 hrs. per day at 5 ft. Approx. 20 footcandles
II	4M-2F Quartz mercury arc. 115 volts. 4.5 amp. Exposure 10 min. per week at 30 inches
III	M (males) = F (females). Non-irradiated controls

COMPOSITE SCORE CARD

	Gen. Appear.	Growth	Post Mortem	X-Ray	Blood Ca	Bone Ash	Total Average
Sunshine	100	100	100	100	100	100	100
I	15	8.3	6.4	14	9.5	20.4	12.3
II	93	85.8	91.6	92.5	75.3	82.7	86.8
III	0	0	0	0	0	0	0

transmitted about 40 per cent of the radiation at λ3000. It was far from an ideal glass for this purpose but was the best available at that time. The quartz mercury arc was used with another group and the third group was the non-irradiated control. Dr. Maughan with a wide experience in this work rated the three groups from seven different viewpoints. The results with sunlight are taken as a basis of comparison. Of course, the quartz mercury arc made an excellent showing. The rating for the non-irradiated controls was zero on each of the seven points. It is seen that the radiation from the tungsten lamp operating 5 hours a day at only 20 footcandles was definitely effective. In this connection it is interesting to note that

Huldschinsky,[44] in an article on the prophylactic use of ultraviolet radiation expresses the opinion that only one-tenth the curative dose is required to prevent rickets. It is also his belief that mild sources of ultraviolet radiation are the most desirable prophylactic against rickets.

It should be emphasized that the chickens were suffering from severe rickets. If the mild ultraviolet radiation of such a low intensity can make an impression upon severe rickets it seems reasonable to conclude that it should have value in health-maintenance in dual-purpose lighting. It is interesting to make an estimate of the radiation shorter than λ3100. The filament of the lamp operated at a color-temperature nearly 3000 deg. K. For each footcandle the radiant power was 0.0083 microwatts per sq. cm. For 20 footcandles the amount would be 0.166 microwatts per sq. cm. However, the bulb did not transmit over one-half of the total energy shorter than λ3100. Therefore, the value was in the neighborhood of 0.08 microwatts per sq. cm. Operating for five hours the exposure was 0.40 microwatt-hours per sq. cm. or 24 microwatt-minutes per sq. cm.

We have obtained other results in sufficient quantity and variety to be certain that the radiation from tungsten filaments is biologically effective and that the threshold value is sufficiently low to obtain results at the levels of illumination considered good lighting practice and for periods well within the daily duration of artificial lighting, particularly during the darker half of the year.

The use of ultraviolet radiation has developed chiefly through the channel of curative therapy. Naturally, high-powered sources of biologically-active radiation were used in order to save time through short exposures. Dual-purpose lighting approaches the subject from the opposite direction—sub-erythemal dosage. Professional therapy is schooled in extra-erythemal dosage and the results of researches are very generally based upon high-intensity short-exposure dosage. Until we inaugurated the experiments with tungsten filaments a few years ago scarcely any thought or research had been

directed upon mild-ultraviolet long-exposure dosage. In this latter field are excellent opportunities for research and there is much encouragement in the results already obtained. The tungsten filament is ready to serve in dual-purpose lighting. Computations and results discussed in the foregoing paragraphs indicate that they can serve very well. However, more biological researches should be co-ordinated with physics. It appears safe to predict that the present demand for high-powered ultraviolet will gradually give way to a realization that mild ultraviolet over the long periods of artificial lighting is valuable.

We have made several attempts to produce erythema by means of tungsten lamps. Failure to do so would not be proof that they are of no value biologically. As already pointed out, the long periods of exposure required with these sources of mild ultraviolet radiation may be so great that physiological repair processes could prevent the production of erythema. Furthermore, the foregoing results indicate that erythema is unnecessary in order to obtain physiological benefit because erythema could not possibly be produced by the low intensities of illumination by means of tungsten-filament lamps in the work of Maughan, Dutcher and Honeywell, and others which we have not mentioned.

We exposed untanned skin close to a 500-watt tungsten-filament lamp for an hour or more without producing an erythema. Of course, a vivid reddening of the skin was produced by the heating effect but no reddening appeared later. We considered focusing upon the skin, by means of a quartz lens, an image of a tungsten filament enclosed in suitable bulb. However, with the quantities of erythema-producing energy available from tungsten filaments, as indicated by the foregoing computations, we believed it should be possible to produce a definite erythema with a tungsten-filament lamp in a special bulb by filtering the radiation through a quartz water-cell. A 500-watt lamp in a bulb of 888 glass (Fig. 55) and designed for a 300-hour life was used in this manner and the skin was illuminated to an intensity of 2380 footcandles. An

exposure of one hour (143000 footcandle-minutes) produced slightly more than the minimum perceptible erythema. An exposure of 90 minutes to the same intensity of illumination (214200 footcandle-minutes) produced a very definite erythema which persisted several days. The exposure to produce a minimum perceptible erythema is seen to be less than that necessary under midsummer sunlight (180000 footcandle-minutes). If the bulb had transmitted all the effective radiation the exposure necessary to produce a minimum perceptible erythema would have been about 90000 footcandle-minutes.

Our studies of the reciprocity law in the production of erythema indicate that it holds over a range of duration of exposures up to three hours at least for the Sunlight (Type S-1) lamp. We believe it is safe to assume for practical purposes that the product of intensity of illumination and duration of exposure can be depended upon over this range. Of course, the absolute value of the effectiveness differs with different sources or illuminants.

The 500-watt tungsten-filament lamp in a bulb of 888 glass operated at a color-temperature of approximately 3000 deg. K. The radiation between $\lambda 2800$ and $\lambda 3100$ per sq. cm. per footcandle from this lamp would have been about 0.00624 microwatts if the bulb had transmitted all this radiation. Assuming that the lack of complete transparency of the bulb reduced the erythemal effectiveness of this radiant energy to 60 per cent, the foregoing figure would be reduced to 0.0037 microwatts per sq. cm. per footcandle. Let us assume that the erythemal effectiveness of the radiation from this tungsten-filament lamp is somewhat greater than that of midsummer sunlight (8540 footcandles) for the same exposure in footcandle-minutes as indicated by our erythemal tests. Then the radiation shorter than $\lambda 3100$ received by a sq. cm. under 8540 footcandles of midsummer sunlight would be about 40 microwatts. This seems to be a fair mean of the measurements and computations in Chapter III which can be considered herewith.

Since obtaining erythema from tungsten-filament lamps we

have learned that similar results have been obtained in Germany where such lamps are being commercialized.

In this connection it should be noted that, notwithstanding the quartz water-cell used in obtaining the erythema with tungsten-filament lamps, the skin was considerably hotter than in the case of the other sources tested. This may make some difference and possibly introduce an unknown factor. However, exactness in this respect is not very important because biological effectiveness must be the final criterion of the use of artificial sunlight. We have already demonstrated this and the computations are helpful as guides to development and use of tungsten-filament lamps and of artificial sunlight in general. Certainly tungsten filaments are promising and with other solid radiators are worthy of more biological research and of actual application in dual-purpose lighting.

CHAPTER XI

Measurement of Ultraviolet Radiation

No region of the spectrum is confronted with such a large assortment of methods of measurement as the ultraviolet. Thermal devices such as the thermopile, radiometer, and the bolometer measure energy or radiant power in absolute values through the heating effect of the absorbed energy. In making determinations of spectral energy or radiation of a very small group of wavelengths, the sensitivity of these time-honored and indisputable devices is often hard-pressed, owing to the small quantities of radiation involved. The well-developed methods of photometry may be brought into use by measurements of fluorescence or phosphorescence excited by ultraviolet radiation. Owing to the chemical activity of this short-wave radiant energy many photo-chemical reactions are available as possible means of obtaining measurements. There are also particularly attractive electrical methods involving photoelectric action. It is not the intention to present an exhaustive discussion of these possibilities but rather to give glimpses into the practical aspects and treat promising examples or avenues. The spectral region of chief interest in a more general use of artificial sunlight is from $\lambda 2800$ to $\lambda 3100$ or $\lambda 3200$. Therefore, this discussion is based chiefly upon the measurement of the total and the spectral energy in this region.

In approaching the general problem it is well to recognize selectivity and non-selectivity in spectral sensitivity of the basic device. Eventually, in the development of a method one or more selective elements may be used with a non-selective device such as the thermopile of the thermal class. Chemical reactions, fluorescence, photoelectric activity and filters are all selective in regard to radiation of various wavelengths. Much of the published data is of limited value owing to the absence

of accurate data pertaining to selectivity. Besides the many difficulties pertaining to physical and chemical methods there are also those due to lack of complete information in regard to the selectivity of biological effects or processes. For example, the spectral erythemal effectiveness is only approximately known and the selectivity of the process of production of vitamin D or of an antirachitic action is not known in detail. With the exception of erythema there is only a fragmentary basis upon which to develop properly selective methods of measuring the total effective radiation. Therefore, ultraviolet radiation must be determined for certain spectral regions of known biological activity. This means that the spectral distribution of energy shorter than λ3100 is of fundamental interest.

For artificial sunlight having the benefits and comparable safety of sunlight the region λ2800 to λ3100 is of particular interest. For good measure it may be permissible to extend this range to λ3200 but, as far as is known at present, biological activity is feeble between λ3100 and λ3200. The maximum of antirachitic and erythemal effectiveness is close to λ3000. It may be at λ2967 or λ3024 for the former and apparently it is near λ2967 for the latter. The maximal action in irradiating ergosterol may be produced by energy near λ2800 but a secondary maximum is possible near λ2700. Inasmuch as the mercury arc is a very common and satisfactory source of artificial sunlight and of biologically-active radiation in general, measurements of relative and of absolute energy in the groups designated as mercury lines at λ2804, λ2967, and λ3024 are important. Therefore, in the light of present knowledge the foregoing are the objectives of measuring devices and methods.

It is claimed by some that anemia is caused by a specific toxin which can be destroyed by ultraviolet radiation from λ2500 to λ4000 with a maximum effectiveness at λ3130. The addition of pure eosin into the bloodstream is said to increase greatly the beneficial effect of ultraviolet radiation in this respect.

The advantages of using non-selective devices for meas-

urements of spectral energy and of total energy in restricted spectral ranges are obvious. The radiometer, thermopile and bolometer can be readily calibrated in units of energy or radiant power per sq. cm. such as ergs per second, microwatts, or milliwatts by exposing them to a standard of radiation. Selective methods cannot be calibrated in terms of absolute energy values excepting by a round-about method which eventually must involve a non-selective method. Furthermore, unless a selective method is exactly similar in spectral selectivity to that of the biological effect, it cannot be used to compare various sources of radiation differing in spectral distribution of energy in the wavelength-range involved. In fact, no selective method can be safely used to compare the energy output from different sources emitting radiation differing in spectral character. If it is accurately selective for a specific biological effect it can be used to measure the specific biological effectiveness of various sources or illuminants. A familiar analogy is a colored glass. Its total transmission and its color differ for various illuminants. Nevertheless, the high sensitivity of non-selective devices required for accurate spectral work in the ultraviolet region calls for training, experience and other facilities which are available only in a few laboratories.

The material of which the optical parts of a spectrometer are made depends upon the region of the spectrum to be studied. In the Röntgen region of shortest wavelength (λ0.1 to λ3) rock salt and calcite crystals are used. For the softer X-rays ruled glass gratings are satisfactory. The short-wave ultraviolet is studied in a vacuum with reflecting diffraction gratings and fluorite prisms. Quartz and fluorite optical systems are satisfactory for ultraviolet radiation longer than λ1850. In the visible region glass prisms and visually achromatized lenses are available. The constant-deviation type of spectrometer in which the angle between collimator and ocular telescopes is constant has gained much favor. The wavelength is varied by rotating the prism. Diffraction gratings can be used. These have the advantage of producing a normal spectrum—uniform wavelength scale—but they also possess the

disadvantage of wasting light owing to the multiple spectra produced. The infrared may be studied with concave metal mirrors. These are achromatic and of high reflection-factor in the infrared and require no lenses. A quartz prism can be used for the short-wave infrared to λ30000; fluorite to λ100000; rock salt to λ150000; and sylvite to λ200000. Photography can be used throughout the entire region excepting the infrared although its accuracy is limited and the technique involves much tedious work.

The dispersed radiation at any wavelength can be measured by several non-selective radiometric devices. The thermopile consists of a series of junctions of two metals; for example, copper and constantan, blackened so that radiant energy is readily absorbed. When one junction is heated by absorbing radiant energy and another junction in series is not heated, a minute electric current is generated. The effect is magnified by using many of the junctions in series of which only half the total number receive radiant energy. The low sensitivity requires a very sensitive galvanometer.

The bolometer, as ordinarily used, consists of a very thin strip of blackened metal in each of two arms of a Wheatstone bridge. The absorption of energy by one of these strips alters its resistance and, therefore, changes the electrical balance. The bolometer is very sensitive to air currents and operates best in a vacuum.

The radiomicrometer is essentially a moving-coil galvanometer having a single loop of wire with a thermo-junction at the ends. One of these receives radiant energy.

The Nichols radiometer consists of two similar thin blackened vanes attached at the ends of a horizontal arm and suspended in a partial vacuum by means of a very fine quartz fiber. The radiation to be measured is permitted to fall upon one of the vanes which becomes warmed by the absorbed energy. It is repelled and the angular displacement is measured. It must have a long period, 30 to 60 seconds, in order to be sensitive. A combination of the thermopile and galvanometer can have a much shorter period.

Detailed descriptions of the technique and accessories involved in the use of these non-selective energy-measuring instruments are useful to relatively few persons. Doubtless, the use of such methods will continue to increase but those newly interested will find it much more profitable to discuss the matter with the few who have had long experience. Outstanding among these is Dr. W. W. Coblentz [38] whose contributions, not only of data but of improvements in devices, are of great value. His vacuum thermopile is a helpful development which we and others are using with success.

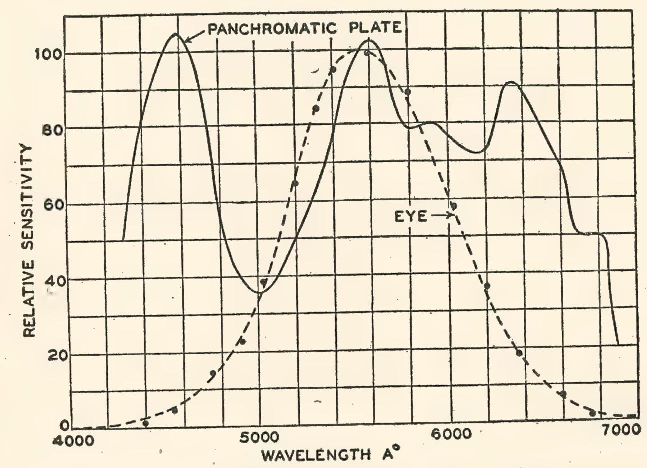

Fig. 43. Selectivity of a panchromatic photographic emulsion of the eye, and of the combined emulsion and a carefully made filter (the small circles).

Nevertheless the present demands severely tax the sensitivity of these non-selective methods. With increasing interest in ultraviolet radiation, often in meager quantity, this entire field of measurement is worthy of the best efforts directed toward further refinement.

In order to modify the selectivity of an inherently selective effect or process so that it may be accurately selective, let us take a case in photography. Filters are commonly used in photography but ordinarily they are not accurately selective because they need not be. However, we desired to photograph objects so that their brightnesses on the final photographic

prints appeared the same as they did to the eye. In fact, photography was to replace visual photometry. We chose a certain commercial panchromatic plate with a spectral sensitivity, as shown in Fig. 43, compared with that of the eye. Filters were made of five different dyes chosen by experience and their densities were determined by experiment. Eventually, all were cemented together with the result that the combined selectivity of the filter and photographic emulsion was practically identical with that of the eye, as shown by the circles on the visibility curve, Fig. 43. The circles on the visibility curve show the closeness of the agreement between the selectivity of the combined filter and emulsion compared with that of the eye. This same problem presents itself in the ultraviolet region excepting that the spectral sensitivities of the biological effects are not as accurately known as the spectral sensitivity of the retinal process.

Inasmuch as ultraviolet radiation produces a large number of chemical reactions it is natural that many of these have been used for measuring its intensity. Most of these methods yield results of very limited value and few of them are more than rough approximations of intensities of ultraviolet radiation. They are devised in order to avoid the refined physical methods which require so much time, apparatus, and experience. Lack of study of these reactions by physical measurements of spectral energy and its effects keeps most of the chemical methods in the class of approximations. Besides this general objection, some of them require technique and apparatus available only in the chemical laboratory. Doubtless some of these reactions can be made quite accurate and useful if thoroughly studied by physical methods. This would result in providing filters, if necessary, so as to limit the radiation to the proper spectral range and to weight the energy of various wavelengths properly. Any of the chemical methods may be standardized in terms of erythemal effectiveness, footcandles, energy, etc., at least for a given set of conditions. Only a few of the simpler methods are briefly described in order to provide a glimpse into this realm of possibilities.

If acidified potassium iodide including a trace of thiosulphate is exposed to ultraviolet radiation in the presence of starch a bluish color develops. The preparation is made as follows:

25 c.c. of 1 per cent potassium iodide
25 c.c. of 5.3 per cent sulphuric acid
1 c.c. of N/400 sodium thiosulphate
A few drops of starch solution.

This test solution is not very stable so it must be prepared often. It is exposed in a quartz test-tube or in an open dish. The time elapsed before the bluish color appears is a relative measure of the intensity of ultraviolet radiation. It is claimed to be an approximate measure of erythemal effectiveness of radiation but it is far from accurate in this respect.

Paper soaked in a 20 per cent aqueous solution of potassium ferrocyanide changes color when exposed to ultraviolet radiation. This color is compared with a standard set determined by exposure to the same source at different distances or for different periods. A given color appears more quickly when exposed to an arc through quartz than through glass. The reaction requires a longer exposure than that which produces erythema. Ordinary blue-print paper may be obtained for this purpose. It is sensitive throughout the near ultraviolet. A series of exposures may be made, then after washing the paper a permanent scale is available.

The bleaching of methylene blue has been used as a measure of intensity of ultraviolet radiation. A 0.1 per cent solution of methylene blue is prepared and 5.8 c.c. of this are added to 30 c.c. of acetone. Enough water is then added to make 100 c.c. Some of this solution is placed in a quartz test-tube and exposed to the ultraviolet radiation. In a given time the bleaching is compared with a set of colors previously standardized by different exposures to known conditions. It is claimed that it is chiefly sensitive to radiation from $\lambda 2000$ to $\lambda 2800$ but is slightly sensitive as far as $\lambda 3250$. The reaction takes place slowly in sunlight but much more rapidly under arc-lamps. The test is simple and requires little skill.

Lithopone, a white pigment used in paints, blackens upon exposure to ultraviolet radiation. We have exposed it in a quartz spectograph and have obtained the spectrum of mercury in black lines from λ2400 to λ3600. Janet Clark has used lithopone mixed with distilled water to a consistency of a thick paste. This is pressed down to a flat surface by means of a transparent quartz plate. She found that its blackening was a fair measure of dosage for erythema for sources widely different in spectral character. In Fig. 45 is shown the spectral sensitivity of lithopone as determined by Pfund. The maximum is at λ3100 and falls off rapidly on the long-wave side. The erythemal maximum is at λ2970. Apparently, lithopone offers promise in the manner in which Dr. Clark has used it. One difficulty encountered is the difference in activity of lithopone obtained from different sources but this may be overcome by obtaining a large supply at one time. With a certain specimen Dr. Clark found that, if the time required at a certain distance to darken lithopone to a gray reflection-factor of 50 per cent be multiplied by 2.1, a perceptible erythema of the skin will result. If that time be multiplied by 0.153, *B. coli* will be killed at the same distance from the source of radiation. The inverse-square law holds when the darkening of lithopone to a reflection-factor of 50 per cent takes place in six minutes or less. At distances where the rate of darkening is slower, the time required is greater than that computed from the inverse-square law.

A solution of oxalic acid (6.3 grams) and uranyl sulphate (4.27 grams) has been used, but it is more or less sensitive throughout the region from λ2000 to λ4000. After exposing it to ultraviolet radiation it is titrated against a 0.1 normal solution of potassium permanganate. The result is stated in terms of quantity of oxalic acid decomposed.

These are a few of the simpler and more promising chemical methods but none of them provides an accurate measure of the biologically-active radiation. Of course, there seem to be several biological reactions which must be taken into account, so that no method could be expected to measure all of

them accurately. All that can be hoped for is a measure of the energy in a spectral range such as λ2800 to λ3100 or λ3200, excepting in the case of a method designed to predict the effectiveness of radiation for a specific biological reaction. When enough filters are available which isolate bands in the ultraviolet, such as Corning red-purple, these chemical methods as well as photometric and electrical methods may be more readily refined. In fact, with a selection of filters available, photographic papers and particularly blue-print paper may find many applications in which they may serve simply and satisfactorily.

Photography of spectra by means of quartz spectrographs is very useful in obtaining qualitative data pertaining to the radiation from sources and the spectral transmission and reflection of various substances. There are many pitfalls in applying photography to spectroscopy. Scattered light is not recognized without a good deal of experience but it can often be overcome by the use of proper filters. In photographing continuous spectra scattered light is particularly annoying and overexposure may result in misinterpretations. With such precautions and the proper accessories very useful quantitative data can be obtained with fair accuracy. Spectral transmission and reflection data are readily obtained. A quartz mercury arc after operating for some time is supplied with constant voltage. A series of spectrograms of this radiation is made, covering a range of exposures throughout the useful latitude of the photographic emulsion. A similar series of known exposures is made through the transmitting substance. By a careful comparison of the two series, taking into account exposure-times, the spectral transmission of the substance is obtained. Spectral reflection data are obtained by comparing the reflection spectra from the substance with those from a non-selective reflecting medium.

Owing to the extensive development of photometric methods and the relative simplicity of the eye as an appraising instrument, fluorescence and phosphorescence produced by ultraviolet radiation are attractive possibilities. Fluorescence does not involve the element of time so that it offers less com-

plexity than phosphorescence. Fluorescence grows to its full brilliance practically instantly but phosphorescence requires time to grow and to decay. Furthermore, the previous history of a fluorescent substance is of little or no consequence, but phosphorescence must be thoroughly destroyed by infrared or other means in order to bring it to a standard condition.

A great number of materials fluoresce. In fact, with a fairly delicate experimental set-up it is difficult to find substances which do not fluoresce slightly, at least under ultraviolet radiation of some wavelength-range or other. Solutions of dyes, salts and other substances can be investigated readily by turning a spectrograph on its side and projecting the spectrum so that it focuses upon the upper surface of the solution in an open dish. For such a purpose a simple spectrometer can be made with two quartz lenses and two prisms in a train. We have studied hundreds of such solutions in the past but not from the present viewpoint of isolating radiation shorter than λ3100 or λ3200. Fluorescent liquids should not be overlooked for laboratory work where the inconvenience can be minimized.

Among the common substances which fluoresce quite freely in solution are

Anthracene in benzol
Eosine in water or alcohol
Esculin in alcohol
Fluorescein in water slightly alkaline
Naphthaline red in alcohol
Quinine sulphate in water
Resorcin blue in water
Rhodamin in water

Most of these will fluoresce fairly well in glass test-tubes but they can also be used in open dishes or quartz containers. It is interesting to interpose a filter such as one of the Corning red-purple glasses, Fig. 49, which transmits ultraviolet radiation longer than λ2500 but not much visible radiation. Solutions of these can usually be successfully applied to white paper or to glass. A white cardboard sprayed with the anthracene solution fluoresces a brilliant blue-green when illuminated by radiation from a quartz mercury arc strained through one of the red-

purple ultraviolet-transmitting filters. By projecting the images of sources such as the Sunlight (Type S-1) lamp—a tungsten mercury arc—upon such a fluorescent screen using quartz lenses and various filters, an interesting demonstration of the ultraviolet emission from various parts of the source can

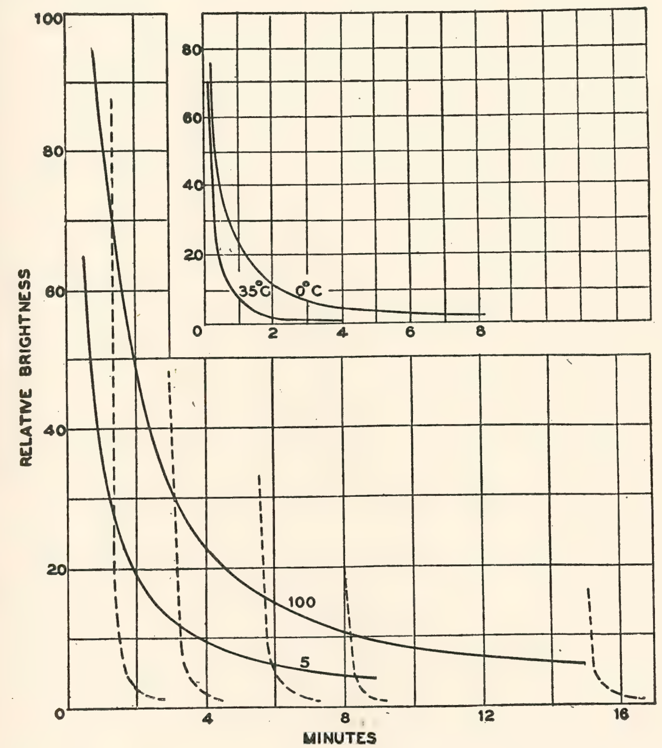

FIG. 44. The lower curves illustrate natural decay of phosphorescence in zinc sulphide and the extinction by infrared radiation for two intensities of the exciting radiation. The upper curves show the influence of temperature.

be made. Of course, such fluorescent filters are commonly used for rendering ultraviolet spectra visible.

Phosphorescent materials have possibilities for measuring ultraviolet radiation but the time-element involved in the decay of the brightness introduces complexity. We have experimented with some of these in the past by noting the time required after excitation for the brightness to decay to a given

brightness. This varies with the initial brightness which depends upon the temperature of the substance and the intensity and spectral character of the exciting radiation. The decay of phosphorescence is very rapid at first then it decreases more slowly, as indicated in Fig. 44, for zinc sulphide. Ives and the author studied this material extensively. We found it quite possible to standardize the extinction by means of infrared radiation so that the phosphorescence always exhibited the same rate of growth and decay. The infrared was obtained from radiation emitted by a carbon filament filtered through a red glass and a cell containing iodine dissolved in carbon bisulphide. The lower curves in Fig. 44 are typical decay curves of phosphorescence excited for the same period by two relative intensities of radiation, 100 and 5 respectively, from a quartz mercury arc. The effect of a one-second flash of infrared is a sudden flash-up of brightness followed by a very rapid decay of brightness to a low value. The upper curves show the influence of temperature of the phosphorescent material. At 35 deg. C, the decay is more rapid than at zero deg. C. In general, temperature must be taken into account.

An inexpensive phosphorescent paint contains calcium sulphide. Usually, it is not very sensitive and the blue phosphorescence is of low visibility. The phosphorescence of zinc sulphide appears yellow-green and is of high visibility. The activity of many phosphorescent materials deteriorates slowly with age, apparently being involved with the decrease in crystalline material which changes with time or environment. Owing to the time-element, the effect of temperature, and the need for eliminating or standardizing the influence of previous history of the substance, phosphorescence is not generally attractive for measuring ultraviolet radiation.

Among the fluorescent solids, glasses are attractive from the viewpoint of devising photometers. Uranium glass which fluoresces a yellow-green is commonly used for detecting ultraviolet radiation and for focusing this part of the spectrum in spectrographs. As is well known to those experienced in spectral research, the fluorescence in uranium glass is produced

by radiation throughout the ultraviolet region and even by violet and blue rays. The relative effectiveness of energy of various wavelengths in exciting this fluorescence is shown in

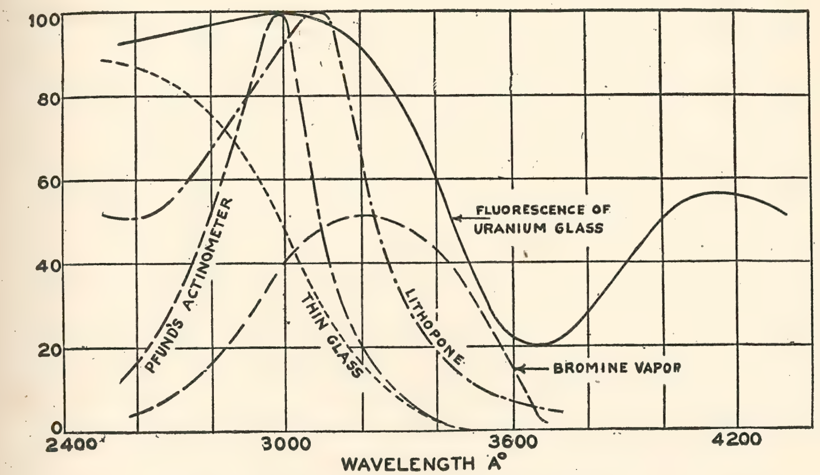

FIG. 45. Spectral sensitivities of uranium-glass fluorescence and of the darkening of lithopone; the spectral transmission of bromine-vapor; the spectral absorption of thin ordinary glass; and the selectivity of Pfund's actinometer (Fig. 46).

Fig. 45 as determined by Pfund.[35] It exhibits an interesting minimum near $\lambda 3700$.

In a search for filters which could be used in connection

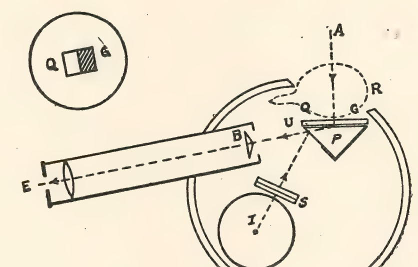

FIG. 46. Diagram of Pfund's actinometer.

with uranium glass in order to filter out the visible and long-wave ultraviolet radiation, Pfund found bromine-vapor fairly satisfactory. He filled a bulb of thin glass with this and the

combination of the selectivities of the thin glass, the bromine-vapor and the uranium glass produced a resultant selectivity approximating that desired. The bulb of bromine-vapor was interposed, as indicated in Fig. 46, between the uranium glass *U* and the source of ultraviolet radiation *A*. The fluorescent surface was viewed obliquely through the biprism *B* and eye-piece *E* in order to intensify the brightness, and this brightness was compared with a variable one as in any ordinary photometer.

In studying the problem, it was seen that the products of the corresponding ordinates of the curves for uranium and bromine-vapor in Fig. 45 yielded a curve differing considerably from the Hausser and Vahle spectral erythemal curve which he was attempting to reproduce. In order to bring about a closer agreement one-half the surface of the uranium glass was covered with a plate of clear glass *G* and the other half with a plate of quartz *Q*. The difference between the brightnesses of the fluorescence from the quartz-covered and glass-covered halves of the uranium glass is due to that portion of the ultraviolet radiation which does not pass through the glass plate. As Pfund stated, the arrangement is essentially equivalent to a filter whose transmission curve is the absorption curve. In the final arrangement, the prism *P*, Fig. 46, is cemented to the uranium glass with Canada balsam. The sides of the prism *P* are blackened as shown so that they absorb the visible radiation which enters the prism. The comparison source of illumination is a small tungsten lamp *I* which illuminates a diffusing screen. The yellow-green filter *S* eliminates color-difference. The image of the brightness of *S* is reflected from a part of one face (not blackened) of *P* so that it is superposed over the brightness of the lesser fluorescence under the glass *G*. By varying the current through *I*, the brightness-match can be made. The calibration then is made in terms of the current. The variable brightness can be obtained in many simple ways.

The maximum of sensitivity of Pfund's complete actinometer is seen in Fig. 45 to be near λ2970, the maximum of

erythemal effectiveness. The general shape of the spectral sensitivity curve is similar to that of the spectral erythemal curve. Certainly for artificial sunlight and for any artificial sunlight whose short-wave limit is near λ2800, this device is promising. Pfund found it to be quite sensitive in the measurement of the biologically-active radiation in sunlight throughout

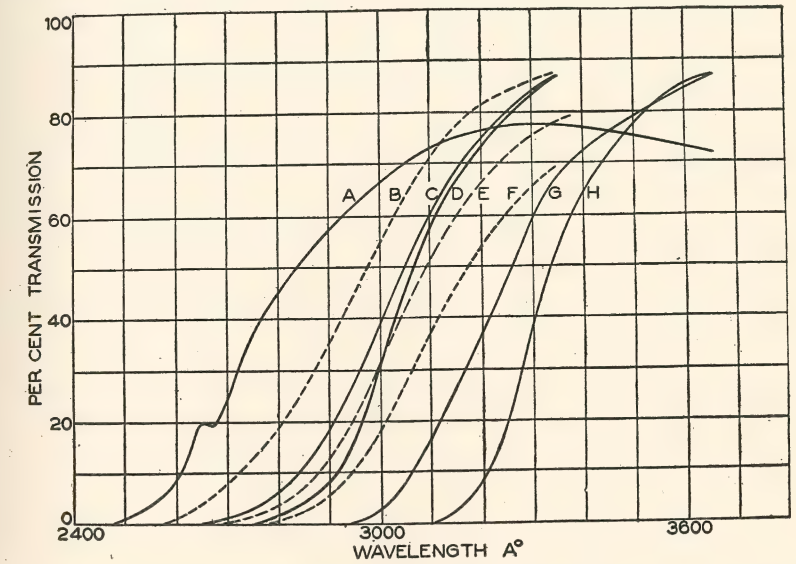

FIG. 47. Spectral transmissions of a series of useful filters for measuring biologically-active radiation and for determining its effects.

A	Corning red-purple ultra	4.21 mm.
B	Microscope cover-glass	0.18
C	Microscope slide	0.96
D	Corning Pyrex	1.05
E	Two microscope cover-glasses	0.36
F	Three microscope cover-glasses	0.55
G	Corning Pyrex	2.99
H	Corning blue-fluorescing	3.99

the year. Owing to the inefficient transmission of the bromine-vapor he suggests that this be replaced by a thin layer of clear gelatin flowed over the surface of the uranium glass which faces the source of ultraviolet radiation.

This device has been described in detail in order to give an idea of the kind of expedients which must be resorted to in

order to produce a device of proper selectivity. Of course, the nearer the selectivity of the basic phenomenon to that which is to be studied, the fewer or less difficult the steps necessary to obtain an over-all selectivity which is satisfactory. For example, Gage [36] reported a glass which exhibited a blue fluorescence, excited only by radiation shorter than λ3100. Such a selectivity on the long-wave side eliminates the necessity of absorbing the long-wave ultraviolet and short-wave visible by means of other filters as is necessary in the case of uranium if only radiation shorter than λ3100 is to be appraised.

We have studied this Corning blue-fluorescing glass and A. H. Taylor has found the fluorescence to be intense enough to be measured by means of a photoelectric cell when the glass is at a distance of several meters from a quartz mercury arc or a Type S-1 tungsten-mercury arc. The spectral transmission of the glass is shown in Fig. 47 with a number of other filters representing various spectral cutoffs which we used in other researches, such as the determination of the spectral erythemal curve. Taylor found that a specimen of this blue-fluorescing glass 3.99 mm. thick transmits 3.5 per cent at λ3132. It is seen that some of this radiation passes entirely through the glass because the fluorescence produced by this spectral energy is visible in the body of the glass. The fluorescence due to energy of shorter wavelengths is confined close to the surface where the energy is absorbed. By grinding the glass very thin much of λ3100 would be transmitted and would not contribute to the production of fluorescence. In this manner the selectivity at the long-wave side could be increased. On the other hand, with a thick specimen all the energy of the prominent mercury line λ3130 could be utilized in the production of fluorescence.

The spectral sensitivity of this blue fluorescence is indicated in Fig. 52. The curve *R* shows the improvement in selectivity by filtering the radiation through Corning red-purple before it reaches the fluorescing glass. Curve *B* represents the results through a combination of red-purple and thin Pyrex. *R-B* is the difference between the values of curves *R* and *B* and is seen to be fairly selective in appraising mercury

arcs at least. On the short-wave side, a glass of Corex D of such thickness that it does not appreciably transmit radiation shorter than λ2800, limits the combined selectivity sufficiently for some practical purposes. In fact, the short-wave side offers no great difficulties because from a variety of glasses one of approximately suitable spectral cutoff may be selected.

The apparatus as Taylor has developed it is illustrated in the upper part of Fig. 48. Radiation from a source *S* at a distance enters through filter *F*, if such is used, and is incident

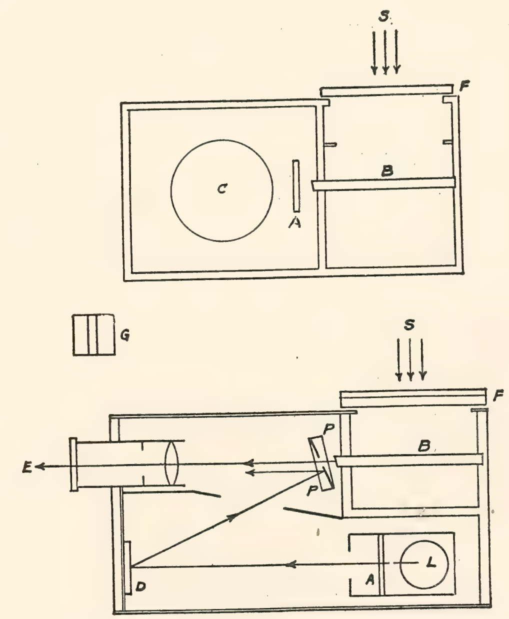

Fig. 48. Taylor's fluorescent photometer.

upon the blue-fluorescing glass *B*. The latter is tightly held in the walls of a box lined with black velvet. The visible radiation may be reduced by a red-purple filter *F* but this is unnecessary. The radiation which passes through *B* unused is absorbed by the velvet lining. The blue fluorescence in *B* is viewed through the edge of the glass slightly obliquely to the upper surface of *B*. Another precaution against stray light is a blue filter *A*. The vacuum caesium photoelectric cell *C*

measures the intensity of fluorescence. This cell need be sensitive only to visible radiation and, therefore, it may be any suitable cell such as potassium hydride with a glass bulb. The photoelectric cell is adequately sensitive for the application of this device to requirements of practice.

The eye and a photometric arrangement may be substituted for the photoelectric cell and galvanometer as shown in Fig. 48. Two thin glass prisms *P* are combined as shown. One of these has a silvered surface with a strip scraped off. The prisms are cemented together with Canada balsam and the edge of the fluorescent glass is viewed through this slit in the silvered surface. An image of the diffusing glass *D* illuminated by a tungsten lamp *L* is reflected toward the eye *E* by the silvered surface. The image from the glass surfaces is reflected at such an angle that it is not seen by the eye. The combined prisms *P* are so placed that the reflected image of *D* from the front and rear surfaces is not seen by the eye. The color difference is eliminated by a blue filter *A*. The photometric field as seen by the eye is illustrated in *G*. We have also made this fluorescent attachment for the Macbeth illuminometer and have made a variety of simple detectors of ultraviolet radiation using this fluorescing glass.

The fields of photoelectricity, fluorescence and photochemical reactions have assumed a new practical interest since measurements of ultraviolet radiation, particularly between λ2800 and λ3100, have become important. Although exploration of the possibilities is going on, no final thoroughly accurate device can be made until the spectral sensitivities of the various biological effects are known. As already stated, the best that can be done at present is to produce devices whose combined selectivity, including filters if used, approximates the spectral erythemal curve and also devices which measure the amount of radiation in certain spectral ranges, for example from λ2400 to λ3100, λ2800 to λ3100, λ2950 to λ3050, and very narrow ranges near λ2967 and λ3024, respectively. We have found that with the mercury arc, filtered through a glass with short-wave cutoff near λ2800, the erythemal effectiveness of the

total radiation is closely proportional to the relative amounts of energy either in the neighborhood of λ2967 or of λ3024.

In the class of photometric devices the common photometer or footcandle meter is very useful in measuring relative amounts of ultraviolet radiation which are biologically active. Of course, as adequately discussed in other chapters, different sources or illuminants cannot be compared in this respect without the determination of constants. Certainly, as one goes

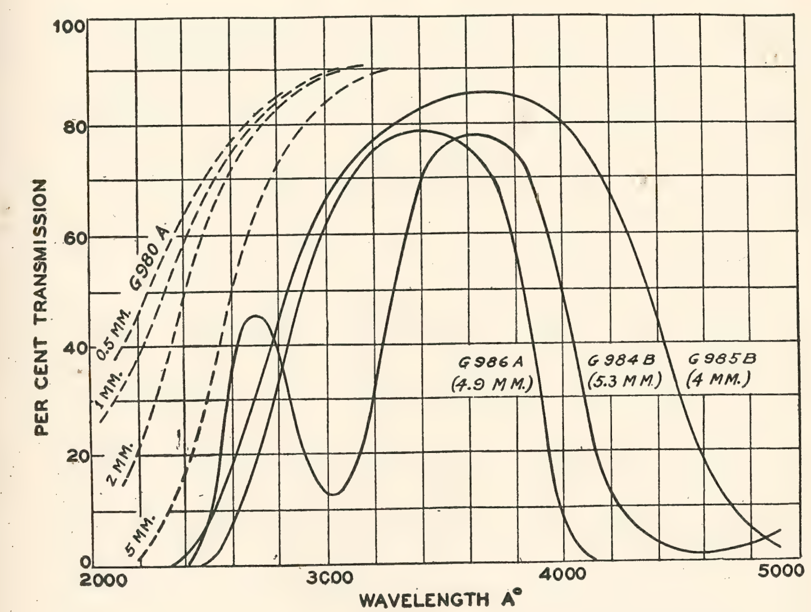

FIG. 49. Spectral transmission of Corning colored filters and of a colorless glass quite transparent to ultraviolet radiation.

deeply into the matter of measuring devices and methods, the practicability of our erythemal-footcandle basis is more and more emphasized. In the present state of incomplete spectro-biological knowledge our method, devised as a foundation for general use of artificial sunlight, has much merit also as a basis for laboratory research. At least we use a biological effect which is basically and practically important. Even absolute energy-measurements must be interpreted eventually in terms of a biological effect. In fact, our interest is not primarily in a

selective device or method which will measure spectral energy within certain wavelength limits, but one which will be a measure of erythemal effectiveness in order to eliminate the tedium of actual measurements of erythema.

As the other biological effects become well known, physical instruments can take the place of rats, chickens and human beings. By measuring the erythemal effectiveness or energy within certain narrow wavelength limits, antirachitic effectiveness can be predicted with fair accuracy. Relatively simple improvements can be applied to existing devices to render them sufficiently accurate for antirachitic application. The spectral sensitivity of ergosterol in the production of vitamin D is less known. Usually, too much weight is given to the absorption curve of ergosterol (Plate II). Of course, the activating radiation is among that absorbed, but what are the wavelengths and what is their relative activating power? Even without the answers to these questions, it is possible to devise measurements between certain spectral limits which by experiment can be established as measures of the relative activating power of the total restricted radiation from a source.

The electrical methods for measuring ultraviolet radiation are generally based upon photoelectric effect. It appears that for every substance there are radiations of a certain spectral range which will produce a kind of trigger-action in atoms causing them to eject electrons. The atoms losing the electrons become positively charged. In order for photoelectric emission to occur, the wavelengths of the incident radiation must be less than the critical or threshold wavelength. This is not the same for different substances. Fortunately, from our present viewpoint the critical wavelength for most substances is in the ultraviolet region of the spectrum although in some cases it is in the visible region and for cæsium it is claimed by some to be in the infrared. Although experience has taught us to be somewhat skeptical of some data, the commonly accepted values of critical wavelength for various metals appear to be approximately those given in Table XXIX.

The emission of electrons from a substance receiving radiation depends very much upon the cleanliness or purity of the surface of the substance. Therefore, films of gas, oxide, etc. must be avoided by polishing and cleaning and enclosing them in a vacuum. The strength of the photoelectric current from the illuminated surface is proportional to the intensity of incident radiation. It varies with the substance, the wavelength of incident energy, the age of the surface, the gas content, and possibly with temperature. Available values for threshold wavelengths are considerably in doubt in many cases; therefore, the data in Table XXIX are to be considered more or less of a pictorial guide to the performance of metals cleaned and

TABLE XXIX

Approximate Values of Longest Wavelengths Which Produce Photoelectric Emission from Clean Metals in a Vacuum

Aluminum	λ3900	Lithium	λ5800
Barium	3200	Magnesium	5500
Bismuth	3140	Nickel	3050
Cadmium	3130	Platinum	2815
Cæsium	7200	Potassium	6500
Calcium	4000	Selenium	2670
Carbon	2615	Silver	3315
Copper	2900	Sodium	5830
Iron	2915	Tin	3285
Lead	2980	Uranium	3200
		Zinc	3425

polished before being placed in a vacuum. Some of the values are rounded averages of data obtained by different observers. In case there was any rapid shift in critical wavelength with age the longer wavelength is given. Some idea of the wavelength of maximum sensitivity is gained by taking two-thirds of the critical or threshold wavelength. This relationship seems to hold approximately for many metals. The wavelengths representing the threshold and the maximum sensibility are merely preliminary guides in the choice of metals for photoelectric effect. They vary greatly in magnitude of photoelectric emission. With the alkali metals, measurable currents have been obtained with radiant power of 3×10^{-9} ergs per sq. cm. per

second for blue light and with one-hundredth of this value for orange light. The greatest charge liberated per calorie of incident radiation is about 0.01 coulomb; for platinum λ2000 the charge liberated is 3×10^{-5} coulomb per calorie; for aluminum λ2200 it is 23×10^{-5}; for sodium λ3700 it is 171×10^{-5}; for sodium λ2300 it is 330×10^{-5} coulomb per calorie.

A quartz envelope must be used if the photoelectric cell is to be used for measuring ultraviolet radiation throughout the ultraviolet region as far as λ2000. Envelopes of other ultraviolet transmitting media, such as Corex D, are suitable for the measurement of radiant energy between λ2800 and λ3100.

TABLE XXX

WAVELENGTHS OF MAXIMUM PHOTOELECTRIC EFFECT FOR VARIOUS ELEMENTS AND COMPOUNDS

(Values obtained by E. F. Seiler)

Li	λ4050	KH quartz	λ4620
Na	4190	KH Pyrex	4570
NaH	4270	Rb	4730
NaH neon	4070	RbH	4810
K	4400	RbH quartz	5070
KH	4560	Cs	5390
KH neon	4380	CsH	5400

(Values obtained in vacuo by others)

Ba	2800	KHg_x	3800
Cd	2500	KNa_x	3900
Cs	4800	KRb_x	4500
CsK_x	4800	Li	2800
$CsNa_x$	4800	Na	3400
$CsRb_x$	4800	$NaRb_x$	4500
K	4400	Rb	4670

Cells can be obtained which are sensitive to any portion of the spectrum from λ2000 to λ10000, although no cell is best suited for the entire range. The absolute sensitivity of a substance must be considered in any given spectral region. Seiler [37] studied 30 photoelectric cells including all the alkali metals and the hydrides of Na, K, Rb, and Cs. She found that as the atomic weight of the alkali metal increased the maximum sensitivity decreased, the resonance peak broadened and the wavelength of maximum sensitivity shifted toward longer wavelengths. Her results for wavelengths of maximum sensitivity for various elements and compounds are presented in Table XXX with other results appended. The voltages applied varied chiefly from 100 to 3000 volts. The envelopes were of common glass containing argon at low pressure, unless otherwise indicated. Inasmuch as the wavelengths of maximum sensibility are well in the spectral region where glass is of highest transmission-factor, the different results obtained in Pyrex and in quartz are not due to spectral transmission of the envelope. Apparently, the presence of an inert gas at low pressure alters the spectral sensitivity considerably.

The data in the foregoing tables are presented for what they are worth. Owing to the influence of various factors it is not surprising that cells made by different persons vary considerably in spectral sensitivity. We have found sodium cells supplied by manufacturers to have maximum sensitivities in the region of λ3000 and λ3100. We have used a sodium vacuum cell successfully for spectral work between λ2500 and λ3000. A cadmium cell is attractive for measuring total radiation between λ2800 and λ3100 because it is not appreciably sensitive to radiation longer than λ3100. Its resultant selectivity can be modified on the short-wave side by means of a proper choice of an ultraviolet-transmitting glass of proper thickness. The envelope for such a cell can be made of the proper glass for properly limiting the short-wave radiation.

The introduction of inert gas at low pressure seems to increase the sensitivity of photoelectric cells very much. We have successfully used a gas-filled potassium cell for spectral measurements throughout the region from λ3500 to λ6600 by resorting to electrical amplification of the photoelectric current. A gas-filled cæsium cell is satisfactory throughout the visible spectrum. With a tungsten-filament source its maximum sensitivity is in the region of λ5400. A vacuum cæsium cell exhibits a nearly linear relation between intensity of illumination and photoelectric current throughout the visible and requires only a moderate voltage to produce saturation of

electronic emission. Although barium, lithium, zinc, magnesium, cadmium, sodium and other cells are available for the middle ultraviolet spectral region, research will doubtless yield many improvements which will be welcome. The growing interest in radiation between λ2800 and λ3100 makes it possible to use new ultraviolet-transmitting glasses as envelopes. This simplifies their manufacture compared with the production of quartz envelopes which are needed if radiation of much shorter wavelengths is to be studied.

Koller [39] has compared the merits of gas-filled and vacuum

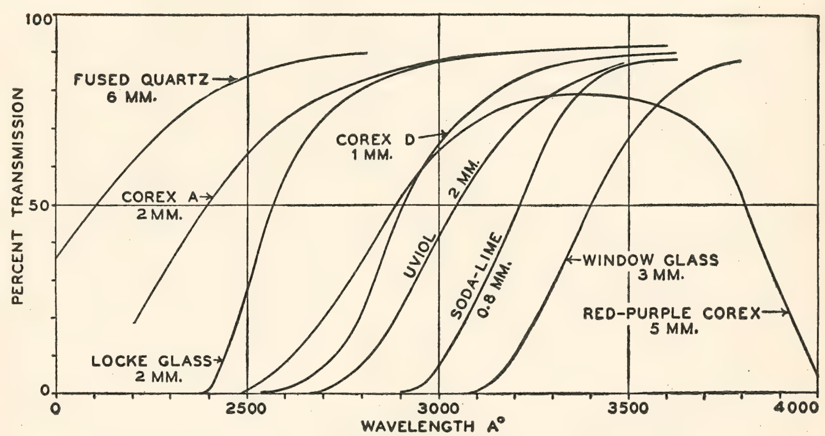

FIG. 50. Spectral transmission of glasses useful as filters.

photoelectric cells and many other researches are available, a digest of which is outside the scope of this treatise.

The photoelectric cell can be used to measure the total energy within a limited spectral range by means of filters or by enclosing it in a sliding box which is used in place of the photographic plate in a quartz spectograph. By having two slides in the plane of the focused spectrum, the spectral range admitted to the cell can be varied. We shift the entire accessory, consisting of cell and variable slit, across in the plane of the spectrum, thereby being able to determine the energy in narrow ranges of the spectrum such as the mercury lines. It is possible to vary the slit in front of the cell to admit such a range as λ2800 to λ3100. When the spectral sensitivity of important

biological effects is accurately determined a miniature template may be inserted into the desired region of the focused spectrum. Such a template would have as ordinates the biological effectiveness of equal amounts of energy of various wavelengths. The abscissæ for use in a prism spectograph must conform to the dispersion. If the curve in Fig. 12 were an accurate representation of the equal-energy erythemal curve, the template would be a miniature of this excepting that the wavelength-scale would be spread out more to adapt it to the dispersion of the prism. We have tried out such templates but, unfortunately, the only spectral biological curve even approximately known is the erythemal curve. Until the exact forms of others

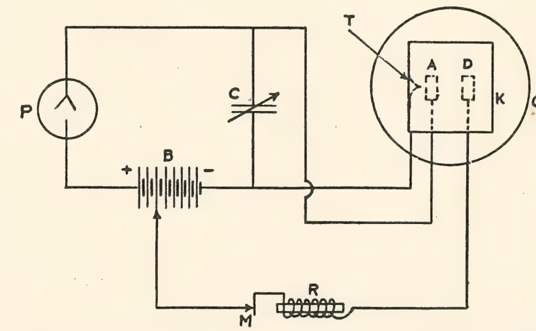

FIG. 51. Diagram of the electrical circuit of Rentschler's ultraviolet-radiation meter.

are determined there is little encouragement to develop the template device.

Rentschler [40] has developed an excellent device which integrates the output of ultraviolet radiation over any desired period and also for a steady source provides measurements of its output. A diagram of the electrical circuit is shown in Fig. 51 in which the battery *B* charges the condenser *C* at a rate determined by the photoelectric current produced in the uranium photoelectric cell when ultraviolet radiation falls upon the cathode of the cell. Heretofore, the rate of charging or discharging of the condenser has usually been measured by means of an electroscope or electrometer. Rentschler introduced a specially designed "glow relay" tube *G* in place of

these devices. The glow relay tube has an iron metal cylinder about one inch in diameter and 1.5 inches long for a cathode *K*. There are two anodes: *A* is a starting anode preferably of thorium metal and *D* is the main anode. A small iron or nickel wire *T* is welded to the cathode so that a short gap exists between it and the starting anode *A*. The position of the starting tip with reference to the two anodes effects the sensitivity.

The main anode *D* is connected to the battery *B* through a relay *R*. The voltage between *D* and *K* is kept below that normally required to start the discharge. When radiation falls upon the cell *P* the photoelectric current charges the condenser *C* and eventually a discharge takes place between *K* and *A*, the cathode resistance of the glow tube is broken down and a current flows between the main anode *D* and the cathode. This operates the relay, registers the count and opens the main circuit *M*. Simultaneously, the condenser is discharged. The radiation, continuing to fall on the cell *P*, charges the condenser *C* and the operation is repeated. The intensity of radiation capable of producing photoelectric current in *P* is proportional to the rate at which the counter registers and the total quantity of effective radiation is proportional to the total number of discharges registered. By means of this device it is possible to measure much less than a thousandth of a microampere.

According to Rentschler the uranium cell does not respond to ultraviolet radiation longer than λ3200. By using an envelope of quartz or of a suitable ultraviolet-transmitting glass this cell and entire device will make a continuous record of the radiation between λ3200 and any desired shorter wavelength.

The Hallberg "erythemmeter," in which a cadmium cell with a quartz bulb is used, has been developed in Germany. The ultraviolet radiation incident upon the cadmium cell generates an electric current which discharges an electrometer. The rate of discharge is indicated by the movement of a pointer over a scale. Different sources or intensities are compared by the time required for the pointer to traverse a chosen portion of the scale. The position of the pointer is adjusted to zero by means of a charging crank and by discharging the electrometer

by touching its terminal one or more times with a lead pencil. The aperture to the cadmium cell contains a shutter and a diaphragm which control the admission of radiant energy. A Heliol glass filter is also provided for filtering out radiation shorter than λ2900, if desired. The cadmium cell supplied with the instrument is claimed to be sensitive from λ2450 to

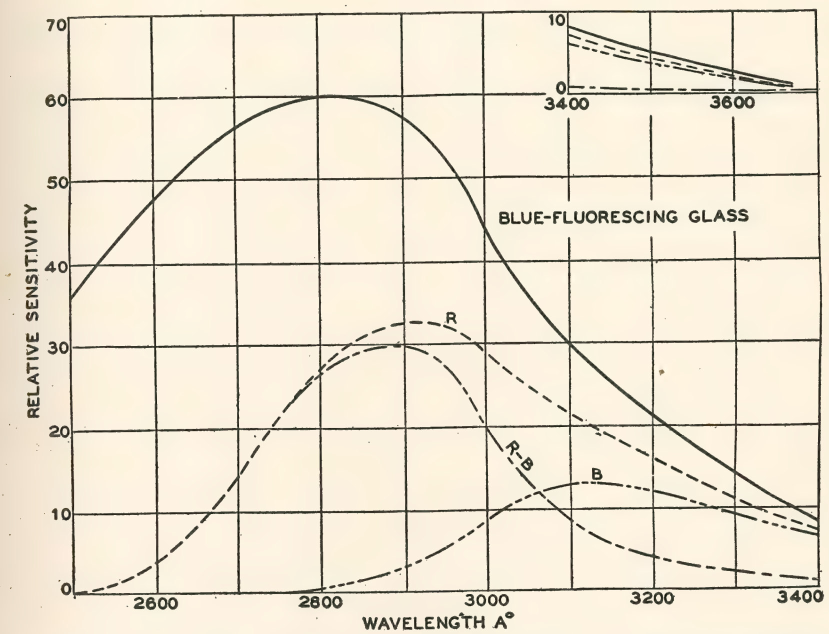

Fig. 52. Showing the relative spectral sensitivity of the blue-fluorescing (Corning) glass and its selectivity R as modified by red-purple (Corning) ultra-violet-transmitting glass. Curve B is the fluorescence through red-purple and thin Pyrex. The difference between the values of R and B is the curve R-B which is fairly selective for appraising radiation from mercury arcs. The spectral transmission of the blue fluorescing glass is shown in H, Fig. 47.

λ3130. Therefore, when the Heliol filter is used, the radiation between λ2900 and λ3130 is measured. This range includes the maximal erythemal and antirachitic effectiveness.

The instrument may be standardized in any desired manner, including footcandles produced by a given source or by distance from the source. Sunlight during midday in summer may be used. This varies on different days but an average or a

maximum value may be used. On a clear summer day the pointer moves over one-half the scale in about the same time required to produce a minimum perceptible erythema, provided the diaphragm is fully open and the filter is not used. A quartz mercury arc will discharge the instrument in about a minute at a distance of 30 inches if the diaphragm is fully open and the filter is not used. By means of the diaphragm and filter a wide range of suitable discharge rates is obtainable. (See Table XXXVI, Chapter XIII.)

Owing to the fact that interest in biologically-active radiation must at the present time be directed largely at the region of maximal effectiveness and at spectral ranges such as λ2800 to λ3100 or λ2900 to λ3100, any method which can determine the total energy in a narrow spectral range is attractive. A quartz spectrograph and movable slides over the plane of the focused spectrum can be used satisfactorily with several means of recording or measuring the radiation passing through the opening between the movable slides. As already suggested, a template for this opening can correspond to the spectral effectiveness of radiation for any specific biological effect. Owing to the lack of accurate data pertaining to spectral effectiveness the total energy between certain narrow wavelength limits provides a rough comparison of sources or illuminants.

As already described, we are using a photoelectric cell with adjustable aperture in the plane of the focused spectrum. This may be replaced by a small sphere coated with magnesium oxide. The spectral limits of the energy entering the sphere may be adjusted as desired and a template may be introduced to weight the energy of various wavelengths. A small aperture in the sphere 90 degrees from the aperture through which the energy enters may be used for measuring the energy which enters. A photographic film over this aperture is a suitable recorder which is not appreciably selective throughout the narrow range between λ2800 and λ3100. A photoelectric cell may be used and even a thermopile if the amount of energy is great enough. Such a device may be calibrated by means of a tungsten filament in a quartz bulb, the amount of energy within

the spectral limits being computed with sufficient accuracy for the purpose. This eliminates the necessity of filters and the difficulties involved.

The use of a photoelectric cell in this manner is a very satisfactory means of obtaining spectral reflection- and transmission-factors. Even the selectivity of the cell need not be known. It is only necessary to note the galvanometer readings at a given wavelength when the material is respectively in and out of the path of light. The ratio of the two readings is the transmission-factor in the case of a transparent medium. Satisfactory correction can be made for surface reflection by substituting a piece of transparent quartz. Translucent materials cannot be studied as simply, but they can be placed over the opening of a hollow sphere coated with magnesium oxide on the inside. Reflecting media may be divided into specular and diffusing, with some surfaces, such as oxidized aluminum and unpolished nickel, being between these extreme types. For diffusing surfaces the comparison surface (corresponding to the transparent quartz in the case of transparent media) may be magnesium oxide or any pigment reflecting very highly throughout the ultraviolet region. For other types of reflecting media other obvious expedients may be resorted to.

It is convenient, in using a photoelectric cell in the foregoing manner, to have calibrated filters so that the energy can be reduced when the medium being examined reflects or transmits very effectively. A series of these can be placed on a wheel so as to be moved quickly in place. A simpler compensating filter can be made of Corex D or other suitable glass in the form of a wedge, two or three inches long, very thin at one end, and several millimeters thick at the other. This may be moved by a micrometer screw and calibrated for transmission-factor at various thicknesses and wavelengths. A family of curves of spectral transmission-factors for various thicknesses (micrometer settings) arranged on a chart provides a quick method of obtaining the "filter factor" by which the galvanometer reading is to be divided or multiplied.

In order to reduce possible difficulties introduced by the

variable thickness of the glass wedge, another of fused quartz could be fastened to it in such a manner that the total optical path is more nearly constant. If the quartz wedge is on the side toward the source of radiation it may have its exposed face ground. This gives better results, as a rule, both in the case of spectrograms and energy measurements. It is seen from Fig. 50 that a thin wedge of Corex D would provide a compensating filter over an important part of the spectrum. A thin wedge of one or two other suitable glasses, such as represented in Figs. 47 and 50, would extend the range over a greater part of the spectrum. Such an arrangement makes it possible to determine very rapidly spectral transmission and reflection curves of any medium.

The usual sectored disks are particularly useful with ultraviolet radiation, owing to their non-selectivity, but usually they cannot be used with alternating-current sources.

CHAPTER XII

Electric Arcs

It has long been recognized that electric arcs in general emit large quantities of ultraviolet radiation. Inasmuch as interest in the biological effectiveness of ultraviolet radiation arose first in therapy, these powerful sources of ultraviolet radiation have been studied and exploited. When we consider artificial sunlight for dual-purpose lighting with exposures much greater than those used in professional therapy, the powerful electric arcs do not monopolize our interest. Even the tungsten filament becomes promising in this new field of "mild" ultraviolet over long periods. Nevertheless, the arcs are definitely established as sources of biologically-active radiation and they can immediately enter the new field if equipped with the proper filters so that the radiation is safe for the eyes. They may be used alone or in combination with tungsten-filament lamps. Most of these sources are so well known that detailed descriptions are unnecessary.

The carbon arcs offer a variety of possibilities in ultraviolet output, but we are interested predominantly in the spectral region from $\lambda 2800$ to $\lambda 3100$ in addition to the luminous efficiency. The carbon arcs have the disadvantage of complexity and frequent replacement of carbons. The latter may be impregnated with a variety of compounds which emit more or less ultraviolet radiation in various spectral regions. In Plate IV are shown the spectra of a series of different carbons supplied by the National Carbon Co. It is seen that the amount of ultraviolet radiation between $\lambda 2800$ and $\lambda 3100$ varies considerably. For example, the C carbon emits a great deal of energy in this region and the Sunshine carbon is much milder. In Fig. 53 is shown the spectral distribution of energy as determined by Greider and Downes,[5] from the Eveready therapeutic B carbons

and from the Sunshine carbons which are sold for general use. It is seen that with an ultraviolet-transmitting filter having a short-wave cutoff at λ2800, the B carbon supplies a great deal more safe and effective radiation than the milder Sunshine carbon.

In Table XXXI a summary of data by Greider and Downes [5] is presented for direct sunlight in October and November and for radiation from Sunshine carbons operated in various equipments and filtered through a Corex D filter 2 mm. in thickness. In Table II, Chapter II, their value for energy shorter than λ3100 in fall sunlight has been discussed and correction to midsummer sunlight has been considered. Apparently, the maximum value near sea-level for radiation shorter than λ3100 in

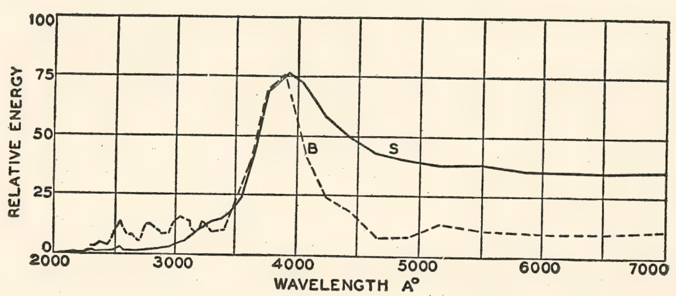

Fig. 53. Spectral distribution of energy from Sunshine carbons (curve S) and from therapeutic B carbons as determined by the National Carbon Co.

midday midsummer sunlight is between 25 and 50 microwatts per sq. cm. on a clear day. The arcs considered in Table XXXI were affected unfavorably by the Corex D filter 2 mm. thick which transmitted only one-third the radiation at λ3000, approximately the maximum of erythemal and antirachitic effectiveness. Furthermore, these Sunshine carbons do not emit as much ultraviolet radiation as some of the other more highly impregnated carbons. Our erythemal tests show that at thirty inches from the Eveready twin arc without a filter the effectiveness of Sunshine carbons is greater than that of midday midsummer sunlight. With the Corex D filter 2 mm. thick only the very high-amperage arc in Table XXXI compares favorably with fall sunlight which is considerably less effective than mid-

summer sunlight. Doubtless, a part of the discrepancy is due to the uncertainty of energy measurement in which filters are used, owing to the undefined spectral limits.

The average percentages of total solar radiation measured in various spectral ranges as obtained by Greider and Downes in October at Springfield Lake, O., and in November at Cragmor, Colo., are as follows:

Shorter than λ3100	0.015 per cent
λ3100 to λ6500	35.5 per cent
λ6500 to λ14000	44.6 per cent
λ14000 to λ120000	19.9 per cent

These results compare very well with those presented in Table VI, Chapter IV, which have been computed for noon sunlight and a clear dry atmosphere.

TABLE XXXI

Radiant Power in Various Spectral Ranges in Fall Sunlight at the Earth's Surface and at a Distance of 30 Inches from Eveready Sunshine Carbons with Corex D Filter 2 mm. Thick (Greider and Downes [5])

	Microwatts per sq. cm.			
	λ2900 to λ3100	λ3100 to λ6500	λ6500 to λ14000	Total
Sunlight, Oct. and Nov.	14.0	3214	4045	9070
Eveready Twin Arc 12 amp. 28 + 28 volts	0.36	184	229	944
Perkins Twin Arc 20 amp. 35 + 35 volts	0.77	358	239	1095
Macbeth Arc-lamp 30 amp. 58 volts	3.62	1370	1162	4260
Macbeth Arc-lamp 67 amp. 82 volts	15.48	4470	2490	11500

The mercury arcs have long been used in biological and chemical applications. These may be divided into two classes: high-pressure arcs in quartz and low-pressure arcs, such as the Cooper-Hewitt mercury vapor lamp, with glass tubes. The latter are now being equipped with special ultraviolet-transmitting glasses, such as Corex D and 888 glasses (Fig. 55). In considering these for artificial sunlight, the radiation longer than λ2800 is of primary interest. In the biologically-active spectral region the quartz mercury arc radiates strongly in

groups of wavelengths designated as λ2967, 3024, and 3130; less strongly at λ2804, 2894 and 2925; and weakly at λ2820, 2834 and 2852. The relative energy in these wavelengths depends upon the temperature, vapor pressure and current density. In general, the ultraviolet output increases with current input or temperature. Several per cent of the total energy emitted by the quartz mercury arc is shorter than λ3100.

In contrast with the low-pressure glass-tube Cooper-Hewitt mercury arc, the quartz mercury arc operates at temperatures, in certain parts of the arc, approaching the softening temperature of fused quartz—1400 deg. C—and at a vapor pressure above atmospheric. Under these conditions of temperature and pressure, the discontinuous spectrum of mercury is augmented by a continuous spectrum of incandescent mercury vapor. This, combined with the selective absorption of the luminous mercury vapor, accounts partially for the shift of the relative radiation intensity toward longer wavelengths. The quartz mercury arc starts with high current and low voltage when it is cold and the vapor pressure is low. For a given arc, the starting current and the final arc voltage are determined by the series resistance. After starting, the temperature rises and the vapor pressure and voltage increase while the current decreases. Final operating condition depends upon the temperature of the surrounding air and the ventilation of the quartz tube and its neighboring accessories. If the quartz tube is cooled the current increases.

The measurement of energy or radiant power in some of the mercury "lines" or narrow groups of wavelengths stresses non-selective instruments to their limit. From the viewpoint of biological effectiveness, λ2967 and λ3024 are very important. We found that the relative erythemal effectiveness of the total radiation from mercury arcs in Corex D and 690 glass corresponds with the relative energy of either of these lines. Therefore, the measurement of energy of these wavelengths can be of much value. Notwithstanding the slight biological effectiveness of λ3130, it should be taken into account in the study of mercury arcs because of the high intensity of this energy in the mercury spectrum. Doubtless, much of the discrepancy of

filter methods of measurement is due to the degree of inclusion or exclusion of the energy in the group of wavelengths designated as λ3130. A similar but less important condition exists at λ2753. This group of wavelengths is of lesser intensity and, spectrally, is far from the maximum of erythemal and antirachitic effectiveness, although it may be found to be important in the irradiation of ergosterol. The spectrum of the quartz mercury arc is shown on various Plates; and in Plates V-VII the transmission of the radiation from mercury through various filters is shown. In Chapter V the erythemal effectiveness of the radiation from the mercury arc is discussed. That discussion is renewed later in connection with other measurements and with dual-purpose lighting installations.

The relative intensities of the various wavelengths in the mercury spectrum depend upon many factors. The values in Table XXXII were obtained for a quartz mercury arc operating at 115 volts. Under this condition it is rated at 3.5 amperes. This tube was quite new, having been operated about 10 hours. The intensities of some of the shorter wavelengths will decrease somewhat with age.

The exposures necessary to obtain minimum perceptible erythema are presented in Table XXXIII for high-pressure quartz mercury arcs and various glass filters and for low-pressure mercury arcs with tubes of special glass. The quartz mercury arcs of different types and wattages were studied. It is well known that the output of ultraviolet radiation diminishes as the total hours of operation increase. In 3a to 3d the effect of ultraviolet-transmitting glasses (Fig. 55 and Plates VI and VII) is seen. These values prove that radiation shorter than λ2800 possesses considerable erythemal effectiveness. However, the quartz mercury arc is so effective that considerable ultraviolet radiation may be sacrificed by means of filters in order to make it safe for general use without goggles to protect the eyes. In fact, as will be seen later, it will generally be necessary to reduce considerably the erythemal effectiveness per footcandle if the quartz mercury is to be used alone. However, this can be accomplished by combining tungsten-filament

lamps with it in the proper proportion. This expedient not only results in reducing the biologically-active radiation per footcandle so that long exposures, as in general lighting, are safe but also improves the quality of light for general use.

The low-pressure mercury arcs with tubes of special glass are much milder sources of erythemal radiation. In fact, they can be used alone if the quality of light is acceptable. The white porcelain-enamel reflector commonly used with the long low-pressure tubes may be replaced by chromium, oxidized aluminum, or other materials which efficiently reflect ultra-violet radiation. In 4a and 5a it is seen that the absence of

TABLE XXXII

RELATIVE ENERGY OF VARIOUS WAVELENGTHS EMITTED BY A QUARTZ MERCURY ARC AFTER A TOTAL OF TEN HOURS' OPERATION

λ2345	0.47	λ2804	5.8
2378	1.8	2854	0.62
2399	2.0	2894	3.6
2482	4.6	2925	2.8
2537	20.4*	2967	10.4
2576	3.3	3024	22.8
2654	12.3	3132	64.3
2675	6.2	3342	8.1
2700	3.0	3663	100
2753	1.9		

* This line is broad, and the slit of the monochomator probably did not admit all of it. Therefore, energy in this band, perhaps, is somewhat greater than the value shown.

the porcelain reflector did not increase the time of exposure necessary for a minimum perceptible erythema, notwithstanding the great reduction in footcandles at the surface of the skin. This means that the porcelain enamel reflects visible radiation efficiently but absorbs practically all the biologically-active radiation. This has already been emphasized. However, there are special cases where the amount of ultraviolet radiation could be reduced by this means to a safe value without sacrificing visible radiation or footcandles. (See Fig. 19.)

In Table XXXIII the values of footcandles and minutes are for a distance of 30 inches from the skin. The total hours during which the source had been operated before the erythemal tests were made are indicated in parentheses in each case.

The tungsten arc in argon or other suitable gas may have interesting special applications. It is steady and in quartz provides a discontinuous spectrum consisting of many wavelengths

TABLE XXXIII

THE INTENSITIES AND EXPOSURES NECESSARY TO OBTAIN A MINIMUM PERCEPTIBLE ERYTHEMA ON AVERAGE UNTANNED SKIN BY MEANS OF MERCURY ARCS AND VARIOUS ULTRAVIOLET-TRANSMITTING GLASSES

	At a distance of 30 inches		
	Footcandles	Minutes	Footcandle-Minutes
High-pressure quartz mercury arcs			
1. Alpine (new)			
325 watts, aluminum reflector	45	8	360
2. Uviarc (new) 529 watts	72	5	360
3. Uviarc (2000 hrs.) 483 watts	51	14	714
a. Corex D glass, 0.5 mm.	46	21	966
b. Corex D glass, 0.8 mm.	46	28	1290
c. 888 glass, 0.6 mm.	46	30	1380
d. 690 glass, 0.9 mm.	46	32	3310
Low-pressure mercury arcs			
4. Cooper Hewitt (new) 515 watts			
Tube of 888 glass	96	60	5760
a. With porcelain reflector	185	60	11100
5. Cooper Hewitt (new) 515 watts			
Tube of 690 glass	99	91	9010
a. With porcelain reflector	193	91	17560

AVERAGE FOOTCANDLE-MINUTES TO PRODUCE A MINIMUM PERCEPTIBLE ERYTHEMA WITH A NEW QUARTZ MERCURY ARC AND VARIOUS FILTERS (SEE FIGS. 47 AND 49)

No filter	227 FCM
Red purple Corning, 4.21 mm.	724
1 microscope cover glass, 0.18 mm.	1140
1 microscope slide, 0.96 mm.	1696
Pyrex, 1.05 mm.	2138
2 microscope cover glasses, 0.36 mm.	2338
3 microscope cover glasses, 0.55 mm.	3915
Pyrex, 2.99 mm.	15300

from λ3000 to λ2300 as shown in Plate VIII. The continuous spectrum longer than λ3000 is not due to the solid tungsten electrodes but comes from the arc as seen in those spectrograms made at the shorter exposures or lower values of current. At the present time it does not seem likely that the tungsten arc

will have any general application in dual-purpose lighting. Many special arcs and other sources of ultraviolet radiation have been discussed elsewhere.[2]

A number of tungsten-mercury arcs have been developed and patented; however, the only source of this general character which has been commercialized is the Sunlight (Type S-1) lamp, developed by the General Electric Co. It consists of two tungsten electrodes at the terminals of a tungsten filament, as shown in Fig. 54. The lamp starts in any position

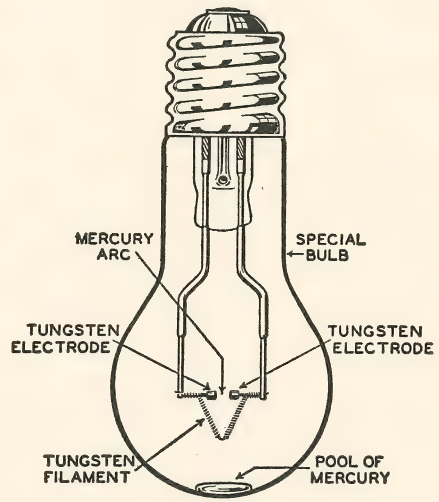

FIG. 54. The Sunlight (Type S-1) lamp consists of a mercury arc between tungsten electrodes at the terminals of a tungsten filament. The bulb contains argon and a pool of mercury which supplies mercury vapor for the arc.

without any moving parts. When the proper voltage is applied the filament heats almost instantly and the arc is completed almost simultaneously. As is true of all mercury arcs, it requires five to ten minutes, depending upon the ventilation, for the radiation to become constant in quality. The biologically-active radiation becomes more intense as the bulb increases in temperature. In fact, we found that a hemispherical cap, placed over the bottom of the lamp in order to screen the source from the eyes, increases the erythemal effectiveness many fold. This increase is at the expense of other desirable

characteristics but it is possible that such an enclosure may eventually be a practical means of increasing the ultraviolet radiation.

The first Type S-1 lamp to be commercialized requires somewhat more than 400 watts, including transformer losses. It is essentially a low-voltage lamp and, therefore, in practice is best suited to alternating current. The transformer must have a drooping characteristic and, for the Type S-1 lamp, must deliver 9.5 amperes at approximately 30 volts for the filament. When the arc is completed the current increases to 30 amperes and the voltage drops to approximately 11 volts.

The Type S-1 lamp, requiring 30 amperes and 11 volts, emits about 6300 lumens at a luminous efficiency of 19 lumens per watt. The mercury arc supplies about 18 per cent of the total lumens, the filament about 7 per cent, and the tungsten electrodes about 75 per cent. The combined light is whiter than that obtained from melting tungsten and it does not have the undesirable quality of light from mercury vapor alone. The color-temperature of the combined light from the Type S-1 lamp in a shallow pendent reflector increases from about 3100 deg. K immediately after starting, to nearly 4000 deg. K after 10 minutes of operation. The light tends to become whiter as the lamp ages. The color of the light from the incandescent tungsten alone is approximately that of an ordinary 500-watt tungsten-filament lamp. The mercury arc in the Type S-1 lamp is very concentrated and its brightness is several times that of the Uviarc—a standard quartz mercury arc. In a quartz bulb the Type S-1 lamp provides an excellent high-intensity source of the mercury wavelengths for spectral work in the middle ultraviolet. Experimental lamps of this type have been made throughout a range of wattages and it is likely that other sizes will find fields of usefulness. In the designation S-1, the letter is the initial of sunlight and the numeral indicates the first lamp of the sunlight type. Other lamps, differing in type but providing useful ultraviolet radiation, may be termed S-2, S-3, etc.

The Sunlight (Type S-1) lamp consists of two primary

sources of energy—incandescent tungsten and mercury vapor. The radiant energy of the former consists of a continuous spectrum of all wavelengths extending from the long-wave infrared well into the ultraviolet region. The mercury vapor emits energy only of the characteristic wavelengths of mercury plus a slight amount of energy due to the fact that it becomes incandescent at the high temperature of the concentrated arc. A source for dual-purpose lighting is safest for general use when the "goggles" are placed upon it. Certainly lighting for health as well as vision cannot be practicable if goggles must be worn over the eyes. The bulb of the Type S-1 lamp serves the purpose of goggles. Of course, proper ultraviolet-transmitting glassware can be used to enclose bare carbon arcs and quartz arcs.

Inasmuch as the bulb of the Type S-1 lamp blackens during the life of the lamp it is of interest to know the effect of this coating upon the output of ultraviolet energy. This has been studied by photographing the spectrum, by measuring the energy of the important wavelengths, and by determining the erythemal effectiveness. All measurements reveal a satisfactory maintenance of the ultraviolet radiation. In fact, there is an increase in erythema-producing radiation for the first 300 hours. Average results for a few lamps tested on constant primary voltage in a shallow aluminum reflector are as follows:

Hours operated	0	50	100	150	300
Relative erythemal effectiveness	100	106	117	127	126

Measurements of the energy of the important wavelengths show a definite increase with life.

The effect of primary voltage is illustrated as follows:

Primary voltage	105	115	125
Relative erythemal effectiveness	60	100	145
Relative energy of $\lambda 2967$	67	100	151
Relative energy of $\lambda 3024$	59	100	168
Relative energy of $\lambda 3130$	64	100	149

In order to ascertain the relationship between energy measurements and erythemal effectiveness, several Type S-1 lamps

were studied under different conditions. The erythemal effectivness was found to be closely proportional to the energy at $\lambda 3024$ or at $\lambda 2967$. However, measurements of total energy not passing through common window-glass were found to be somewhat at variance with the erythemal results.

In connection with the data pertaining to Type S-1 lamps it should be emphasized that, owing to so many variables, these are to be considered approximate and to give only a general view of this new source.

Owing to the sensitivity of the mercury arc to temperature, distance between electrodes, gas pressure, etc., the greatest care is necessary in comparing one lamp with another or in obtaining absolute measurements of spectral radiation. A bare lamp is the best "standard" condition for comparative measurements; still this source is always used in reflectors or other lighting equipment in practice. The spectral transmission of the bulb is very important in establishing a short-wave limit which is safe for the eyes. A number of glasses have been developed and used for bulbs but this lamp was first commercialized with bulbs of Corex D. Other conditions being equal, the ultraviolet output increases with the distance between the electrodes. Forsythe obtained the following average values for 20 Type S-1 lamps in Corex D bulbs:

Distance between electrodes	5.4 mm.
Thickness of bulb	37 mils or 0.94 mm.
Current through lamp	29.7 amps.
Voltage at lamp	11.2 volts

Relative energy of four wavelengths,

$\lambda 3657$	$\lambda 3130$	$\lambda 3024$	$\lambda 2967$
198	100	28	17

In Fig. 55 are shown the spectral transmission curves of two glasses used in bulbs for experimental Type S-1 lamps. The Corex D glass transmits some detectable energy as far as $\lambda 2550$ and the 690 glass as far as $\lambda 2700$. Many tests with intensities as high as 600 footcandles have produced no sign of conjunctivitis even with the Corex D bulbs. At thirty inches from the shallow reflector a minimum perceptible erythema

is produced on average untanned skin by exposures of 8 to 10 minutes to a Type S-1 lamp with Corex D bulb. We have made hundreds of such tests in which the outer membrane of the eye was not protected and have experienced no eye-trouble. The author and others have read for three hours with the white pages illuminated to 300 footcandles without any suggestion of conjunctivitis. Nevertheless, we are interested in providing as much safety to the eyes with the least sacrifice of energy near λ3000. Over-exposure can result in

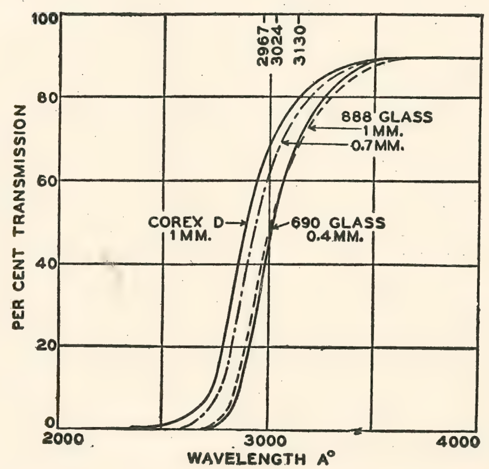

FIG. 55. The spectral transmission of two different glasses used for experimental bulbs for the Sunlight (Type S-1) lamps; also for 888 glass used for various sources including tubes for Cooper Hewitt mercury arcs.

conjunctivitis just as snow-blindness is caused by excessive exposure to sunlight.

In Fig. 55 it is seen that the Corex D transmits about 69 per cent at λ3000 and the 690 glass about 45 per cent. As stated elsewhere, we have found that measurements of energy in the mercury wavelengths λ2967 and λ3024 are quite satisfactory criteria of erythemal effectiveness of the total energy from mercury arcs. According to the transmission-factors for λ3000, the erythemal effectiveness of the S-1 lamp with a Corex D bulb should be about 153 per cent of that of a lamp with a 690 bulb. In fact, this relative value is close to the

average of many tests of minimum perceptible erythema as shown in the following brief summary for many new Sunlight (Type S-1) lamps with 690 and Corex D bulbs tested in shallow aluminum reflectors (G.E. Sunlamp):

	690	Corex D
Thickness of bulb	0.38 mm.	0.97 mm.
Exposure at 30 inches	13.2 min.	8.5 min.
Relative exposure	156	100
Relative erythemal effectiveness	100	156
Footcandles at 30 inches	400	400
Footcandle-minutes	5280	3400

The variation in the footcandle-minutes to produce a minimum perceptible erythema is considerable and depends so much upon the temperature of the bulb that it varies with the ventilation of the equipment. To be conservative we shall adopt the value of 4000 footcandle-minutes for the production of minimum perceptible erythema by a Type S-1 lamp with a Corex D bulb and 6400 footcandle-minutes with a 690 bulb.

The bare carbon arcs and the quartz mercury arcs have been used for years in professional therapy. They have amply won their spurs in this field and, therefore, can enter dual-purpose lighting with proper filters. However, with filters, new proof of biological effectiveness is needed. Enough is known pertaining to the spectral region of biological effect so that erythemal tests combined with physical measurements of energy are sufficient evidence for such sources. We have determined the exposures in footcandle-minutes which produce a minimum perceptible erythema.

The Sunlight (Type S-1) lamp is a newcomer and, notwithstanding the fact that it is a mercury arc combined with incandescent tungsten, its biological value had to be proved by experiment. This has been adequately achieved. Dr. Gerstenberger (Babies and Childrens Hospital, Cleveland) cured rickets in colored babies by a single erythemal dose each week for seven weeks.[48] According to energy measurements by means of photoelectric cells developed as antirachitometers, the Type S-1 lamp with Corex D bulb should prevent and cure

rickets with single weekly exposures of 5 to 10 minutes, which conclusion has been verified in many ways.

Dr. Knudsen (Albany Medical College), from tests on rats in which rickets had been induced by diet deficient in Vitamin D, obtained the following daily dosages for substantial cure in a period of 21 days:

Cod-liver oil	2 drops
Irradiated ergosterol	1/5000 mg.
Uviarc (quartz mercury) at 15 in.	2 minutes
Uviarc at 3 ft.	10 minutes
Direct sunlight in May	150 minutes
Type S-1 lamp in G. E. Sunlamp	
At 3 feet, 290 footcandles	30 minutes
At 9 feet, 38 footcandles	270 minutes

These are only approximate equivalents for curing rickets in rats but they are indicative of the relative value. In this connection it is of interest that, in the opinion of certain authorities, rickets in children may be prevented by about one-tenth the curative dosage.

Dr. Maughan (Cornell University) and other authorities have established the efficacy of the radiation from Type S-1 lamps. Combining such direct biological evidence with the adequate testimony of the spectrum, admits the Type S-1 lamp into the class of therapeutic devices already established by the quartz mercury arc, the therapeutic carbon arcs, and by midsummer sunlight. By using the Corex D bulb, the radiation from the Type S-1 lamp is safe for general use. As seen in Fig. 55, the 690 glass would increase the factor of safety in this respect.

All biological researches up to the present time have been conducted with the Type S-1 lamp in the Sunlamp equipment, consisting of a proper transformer in the base and a shallow oxidized aluminum reflector about 13 inches in diameter. A wire screen across the aperture—a safety feature—absorbs about 25 per cent of the light. With this screen in place, the intensities of illumination along the axis of the reflector at various distances from the aperture are as follows:

1.5 feet	840 footcandles
2	600
2.5	400
3	290
4	175
5	116
6	82
7	61
8	48
9	38

In the hundreds of erythemal tests and energy measurements we have made with Type S-1 lamps, with and without reflectors, we have been impressed with the importance of the reflecting surface. For example, an aluminum reflector which had been poorly oxidized was replaced by another of standard finish. At thirty inches from the aperture of the reflector, the intensity of illumination increased 44 per cent but the erythemal effectiveness increased 200 per cent.

A condensed summary of a private communication from Dr. G. H. Maughan (Cornell University) is of interest for its comparative data. Chicks, 36 hours after hatching, were placed in Pen V containing a brooder supplied with a 60-watt tungsten filament in a Corex D bulb. The temperature of the filament was somewhat higher than in the case of the regular 60-watt lamp. The inside of the brooder was painted green so that there was no increase in the ultraviolet radiation by reflection. The chicks, when they came into the brooder, could be within 3 to 10 inches from the lamp. During the first three weeks the chicks may have remained in the brooder one-third of the time. After that they remained outside most of the time, being exposed to the lamp perhaps one or two hours daily. When outside they received some stray light through openings in the curtain but otherwise received no other antirachitic radiation. No sign of rickets appeared and growth was normal in every way as far as could be determined by X-ray photography, blood and bone analysis, post-mortem examinations, etc.

Chickens six weeks old, suffering from severe rickets due to restricted diet, were divided into four pens:

Pen I received two minutes' daily irradiation from a D. C. mercury arc at a distance of 30 inches.

Pen II received no irradiation.

Pen III received two minutes' exposure daily at a distance of 30 inches from the source in the G. E. Sunlamp containing a Sunlight (Type S-1) lamp in a Corex D bulb. The lamp was operated 10 minutes before the chicks were exposed.

Pen IV received four minutes' exposure daily at a distance of 30 inches from the source in the G. E. Sunlamp, other conditions being the same as for Pen III.

The following summary gives the results obtained in the five pens; the first four involve the cure of rickets by various sources and Pen V, the prevention of rickets by means of the 60-watt tungsten filament in a Corex D bulb. The values are in per cent of normal.

Pen	General Appearance	Growth Records	Post Mortem	X-ray	Blood Calcium	Per Cent Recovery
I	90	85	75	80	95	85
II	0	0	0	0	0	0
III	50	47	50	50	68	53
IV	95	93	90	87	100	93
V	100	100	100	100	100	100

This work not only further verifies the biological effectiveness of the new Sunlight (Type S-1) lamp, but also of tungsten filaments in special bulbs.

Some recent work indicates that a dosage of ultraviolet radiation or of cod-liver oil which prevents rickets is not more than a third or a fourth of the dosage necessary to cure rickets. Estimates with irradiated ergosterol indicate even a much smaller fraction.

CHAPTER XIII

Utilization of Artificial Sunlight

At the outset of our consideration of the development and application of artificial sunlight we chose erythemal effectiveness as a foundation. The more deeply we delve into the subject the more we are convinced that, for the present at least, this is the most practicable basis. Certainly, if we eliminate radiation shorter than $\lambda 2800$ in order to insure safety to the eyes, the remaining erythema-producing radiation is more or less coincidental in wavelength with the biologically-active radiation. Furthermore, the higher degrees of erythema must be avoided, so that perhaps minimum perceptible erythema is the safe maximum for which to design dual-purpose lighting installations. In fact, it is likely that lower values will eventually be considered adequate. Inasmuch as the footcandle will always remain a necessary measure of intensity of illumination, it is logical to provide an erythema-footcandle basis for artificial lighting for health as well as for vision. In Chapter V this basis was introduced and discussed in a limited manner for a few extremely different sources. Bearing in mind the limitations of this basis and the necessity for different constants for various sources or exposures in footcandle-minutes (FCM) which produce a minimum perceptible erythema, the present discussion may be considered to be an extension of the idea into actual new-era lighting practice.

Before discussing the design of dual-purpose lighting we shall assemble the essential data for various sources of artificial sunlight and view briefly some possible methods of measurement which may eventually provide substitutes for tedious determinations of erythema on average untanned skin. Owing to the lack of spectral data pertaining to biological reactions, it has appeared undesirable to make absolute spectral energy

measurements which entail so much tedious work. These cannot be interpreted into biological action. Therefore, measurements have been confined to spectral ranges by various physical methods. Absolute energy measurements in terms of microwatts per sq. cm. are often demanded but usually such demands are based upon an incomplete view of the subject. Aside from the extreme difficulties involved in obtaining them, there is the impossibility at present of interpreting them.

Inasmuch as common window-glass does not transmit the biologically-active radiation, it is natural to utilize this fact in measurements. As a consequence, the fraction of total radiation not transmitted by such a glass has been measured by selective and non-selective methods and the values are considered approximate appraisals of the biologically-active radiation. In order to compare such values with erythemal effectiveness we made such measurements for certain representative sources by means of a vacuum thermopile. In Table XXXIV the first column of values represents the microwatts per sq. cm. per footcandle of the total energy or radiant power from various sources perpendicularly incident upon a surface. Inasmuch as these measurements were made during the winter, we have computed values for midsummer solar radiation from the data of Coblentz and Stair [5] obtained by a similar but not exactly comparable method. However, the values will suffice for comparison.

In the second column of values are the microwatts per sq. cm. per footcandle of the fraction of radiation which does not pass through common window-glass 6.2 mm. thick. In the third or last column of values are given the percentages of the total radiation which is not transmitted by the window-glass. A little study shows that this method does not yield results consistent with the erythemal effectiveness of the various sources. This is partly due to the lack of proper selectivity or weighting of energy of various wavelengths. For example, an inconsistent distinction is made between Type S-1 lamps in Corex D and 690 bulbs, quite contrary to the difference in

erythemal effectiveness as seen in Chapter XII and in Table XXXV. Apparently, the difference in the amounts of energy of λ2967 which is so effective biologically and particularly in producing erythema is only a small part of the total energy not transmitted by window-glass. There is a powerful group of wavelengths at λ3130 and a minor one at λ3342 which are partially transmitted by window-glass but are not effective

TABLE XXXIV

Total Energy or Radiant Power in Microwatts per Sq. Cm. per Footcandle (as Determined by a Thermopile) and the Per Cent of the Total Energy Which Is Not Transmitted by Window-Glass

(A water-cell absorbed the infrared radiation)

Source	Total Energy: Microwatts per sq. cm. per footcandle	Not transmitted by window-glass, 6.2 mm.: Microwatts per sq. cm. per footcandle	Not transmitted by window-glass, 6.2 mm.: Per cent of total energy
Sunlight and skylight *			
Maximum at sea-level	10.0*	0.06*	0.6*
Tungsten filament in 888 glass bulb			
(500 watts, 300-hr. life)	43.8	1.31	3.0
Sunlight (Type S-1) lamps			
With Corex D bulbs	50.0	1.65	3.3
With 690 glass bulbs	49.4	2.17	4.4
Uviarc (quartz mercury arc)			
New tube, 529 watts	25.4	1.42	5.6
Alpine (quartz mercury arc)			
Fairly new, 325 watts	40.4	1.37	3.4
Uviarc (old, 483 watts)	50.0	0.85	1.7

* Values for solar radiation computed from data of Coblentz and Stair [5] obtained by a similar, but not entirely comparable, method.

in producing erythema. Certain refinements are possible which may render such a method valuable, but without these it cannot be considered satisfactory.

Although minimum perceptible erythema is the most definite degree of skin rubescence, the exposures necessary to produce it on average untanned skin can be determined only with moderate accuracy, owing to apparent variations in the sensibility of adjacent areas of skin. Nevertheless, the ex-

posure values may be determined with an accuracy well within the limits necessary, considering the large factors of safety involved in the utilization of artificial sunlight for dual-purpose lighting. This should be borne in mind not only in connection with the values of FCM for MPE, as presented herewith, but also in any consideration of erythema as an important factor in the general use of artificial sunlight. Certainly, these values can be determined with much higher accuracy than most biological effects of ultraviolet radiation. As in the case of any measurements, the accuracy attained depends not only upon the sensitivity of the method, but also upon the number of determinations involved in the final average.

A comparison of other values reveals the same unsatisfactoriness. For example, in Table XXXIV the energy from the 500-watt tungsten-filament lamp which does not pass through the window-glass amounts to 1.31 microwatts per sq. cm. per footcandle. The computations in Table XXVI, Chapter X, indicate that a tungsten filament at approximately the same temperature supplies about 0.012 microwatts per sq. cm. per footcandle of energy shorter than λ3100. In other words, the value in Table XXXIV is about one hundred times that of the corresponding value in Table XXVI. The former value is decreased by the partial absorption of this short-wave energy by the bulb of 888 glass and the latter value is for a bulb of 100 per cent transmission-factor. With these facts in mind it is interesting to compare the values by Coblentz and Stair in Table II, Chapter III. Apparently this explains tne difference between their results and those obtained by others. The measurement of the fraction of energy not transmitted by window-glass seems to yield results of an order of magnitude many times those yielded by computations or direct measurements of the energy shorter than λ3100. Our experience with this method and such comparisons as the foregoing do not incline us favorably to the use of this expedient unless adequate corrections or refinements can be applied.

In Table XXXV are assembled all our determinations of exposures in footcandle-minutes (FCM) which produce a minimum perceptible erythema. Various sources with filters of non-solarizing glass have been studied. Although a number of variables are involved, these values are sufficiently depend-

TABLE XXXV

EXPOSURES IN FOOTCANDLE-MINUTES NECESSARY TO PRODUCE A MINIMUM PERCEPTIBLE ERYTHEMA ON AVERAGE UNTANNED SKIN. PRODUCTS OF INTENSITY OF ILLUMINATION IN FOOTCANDLES AND TIME IN MINUTES

	Footcandle-Minutes (FCM)
Sunlight and Skylight, midday midsummer	180000
High-pressure quartz mercury arcs	
1. Alpine (new) 325 watts, aluminum reflector	360
2. Uviarc (new) 529 watts	360
3. Uviarc (2000 hrs.) 483 watts	714
a. Corex D filter, 0.5 mm. thick	966
b. Corex D filter, 0.8 mm. thick	1290
c. 888 glass filter, 0.6 mm. thick	1380
d. 690 glass filter, 0.9 mm. thick	3310
Low-pressure Cooper Hewitt mercury arcs	
4. Tube of 888 glass, 515 watts	5760
a. With porcelain reflector	11100
5. Tube of 690 glass, 515 watts	9010
a. With porcelain reflector	17560
Tungsten-filament lamp	
6. Bulb of 888 glass, 500 watts, 3100 deg. K.	143000*
Sunlight (Type S-1) lamps, oxidized aluminum reflector	
7. Corex D bulb, 460 watts	3330
a. Conservative average	4000
8. Bulb of 690 glass, 423 watts	6960
a. Conservative average	6400
Carbon arcs	
9. The FCM values for MPE vary over the entire range of the foregoing values depending upon the amperes, volts, filters and type and size of carbons.	

*This value should be reduced at least 30 per cent with a bulb of Corex D glass. Of course it would be further reduced if the temperature of the filament were increased.

able for considering the subject as a whole and for designing installations of artificial sunlight. Of course, when reflectors are used, allowances must be made if they do not reflect the biologically-active radiation quite efficiently. Also, if much of the light reaching the plane of utilization is reflected from

ceiling or walls, some allowance must be made for absorption. These matters are discussed later. It is seen that each source and filter, sometimes including a reflector, has its own value of FCM for MPE (minimum perceptible erythema) ranging from 180000 FCM for midday midsummer sunlight to 360 FCM for a new quartz mercury arc. The actual footcandle values at which the tests were made are found elsewhere. The duration of exposure in minutes in all cases is within the range

TABLE XXXVI

DATA OBTAINED BY FOUR PHYSICAL METHODS HAVE BEEN REDUCED SO AS TO BE COMPARABLE WITH THOSE OBTAINED BY ACTUAL DETERMINATIONS OF MINIMUM PERCEPTIBLE ERYTHEMA, MPE

	Relative Values				
	MPE	CC	BF	SC	TP
Sunlight and skylight, maximum	100	..	..	..	..
1. Alpine quartz mercury arc (100 hrs.)	100	120	143	..	90
2. Uviarc quartz mercury arc (new)	100	114	161	..	87
3. Uviarc quartz mercury arc (2000 hrs.)	100	77	97	..	56
a. Corex D, 0.5 mm.	100	107	108	..	..
b. Corex D, 0.8 mm.	100	124	96	..	..
c. 888 glass, 0.6 mm.	100	83	80	..	..
d. 690 glass, 0.9 mm.	100	121	76	..	..
4. Cooper Hewitt mercury arc, 888 tube.	100	64	57	88	..
a. Same with porcelain reflector	100	64	56	92	..
5. Cooper Hewitt mercury arc, 690 tube.	100	71	57	73	..
a. Same with porcelain reflector	100	72	57	71	..
6. Tungsten filament, 888 bulb	100	88	81	101	86
9. Sunlight (Type S-1) lamp, Corex D bulb	100	153	98	147	109
10. Same with 690 glass bulb	100	167	73	100	144

for which we have proved the reciprocity law holds satisfactorily enough for the present purpose.

Passing over this matter for the present, let us examine the relative values determined by several physical methods. Eventually simple physical methods will be developed to measure erythemal effectiveness and, in fact, biological effectiveness. In Table XXXVI the values obtained by several methods have been reduced so as to be directly comparable with the actual determinations of exposures which produce minimum perceptible erythemas in each case. This is designated as the MPE method and the values in Table XXXV are reduced to

100 in each case in Table XXXVI and the data obtained by the physical methods are reduced to relative or readily comparable values.

CC is the designation for the Hallberg erythemmeter which makes use of a quartz cadmium photoelectric cell. The current generated in this cell discharges an electrometer as described in Chapter XI. The rate of discharge is taken as a measure of the biologically-active radiation. It is seen that the values in this column are only approximately consistent with those in the comparison column, MPE.

BF designates the blue-fluorescing (Corning) glass which we have utilized as a visual photometer as described in Chapter XI. We also measure the brightness of the fluorescence with a photoelectric cell. It is seen that the values in this column are only approximately consistent with those in column MPE. However, this simple method is promising and we are applying refinements which may make it fairly satisfactory. The values are as satisfactory as any obtained by these various physical methods and the method is by far the simplest. (See Fig 52.)

SC designates a quartz sodium photoelectric cell used to measure the fraction of total radiation not transmitted by common window-glass. The values obtained only approximate those in column MPE.

TP designates a vacuum thermopile used to measure the fraction of total radiation not transmitted by common window-glass 6.2 mm. thick. Actually, they are the values in the third column of Table XXXIV multiplied by sixty-six to make them easily comparable with the other values in Table XXXVI. The few values obtained are not encouraging.

We have no doubt that any of these methods can be refined so as to be fairly satisfactory substitutes for the tedious determinations of erythema by exposing average untanned skin. It is unfortunate that we have not had the opportunity to make these refinements. However, the same statement applies to many of the phases of this subject. If we delayed publication until all such matters were clarified, such a treatise would be delayed beyond the period of most usefulness to others. At least, the

data presented in Table XXXVI accomplish the chief purpose of indicating promising avenues of measurement and of showing that physical methods yield results of no value unless they can be interpreted by comparing them with a method involving biological effectiveness and closely related to the biologically-active radiation.

It should be emphasized that all the inconsistency of the

TABLE XXXVII

INTENSITIES OF ILLUMINATION NECESSARY TO DELIVER EQUAL TOTAL AMOUNTS OF ERYTHEMA-PRODUCING RADIATION THROUGHOUT FOUR DIFFERENT PERIODS OF EXPOSURE

	Footcandles 1 hr.	2 hr.	4 hr.	8 hr.
Sunlight plus skylight				
Midday midsummer	3000	1500	750	375
High-pressure mercury arcs				
2. Quartz mercury arc (new)	6	3	2	1
3. Quartz mercury arc (old)	12	6	3	2
b. With Corex D filter, 0.8 mm.	21	11	6	3
c. With 888 filter, 0.6 mm.	23	12	6	3
d. With 690 filter, 0.9 mm.	55	28	14	7
Low-pressure mercury arc				
4. Tube of 888 glass	96	48	24	12
a. With porcelain reflector	185	93	46	23
5. Tube of 690 glass	150	75	38	19
a. With porcelain reflector	293	146	73	37
Tungsten-filament lamp				
6. 888 glass, 3100 deg. K.	2400*	1200*	600*	300*
Sunlight (Type S-1) lamps, oxidized aluminum reflector				
9a. Average Corex D bulbs	67	33	17	9
10a. Average 690 bulbs	106	53	27	13

* These values would be decreased by a Corex D bulb and also by higher filament temperatures.

values in Table XXXVI by any of the methods is by no means chargeable to the method. Many factors are involved and the arcs are not perfectly steady. For this reason the values for the carbon arcs are entirely omitted. The unsteadiness of the mercury arcs is appreciable and they are susceptible to various influences. For this reason, some of the differences in the values are not to be considered inherent in the method. Nevertheless, it is obvious that physical methods, excepting by a

fortuitous accidental selectivity which is unlikely, are to be considered crude measures of erythemal or other biological effectiveness until refined by tediously determined means.

Some of the data pertaining to the sources and filters are omitted from Tables XXXVI and XXXVII but they are numbered to correspond with those in Table XXXV from which the details may be obtained.

It should be noted that sunlight, as viewed on a footcandle basis, contains small rather than large amounts of ultraviolet radiation. It is mild rather than powerful. This has been proved not only by comparative erythemal tests but by energy quantities as seen in Table II, Chapter III, and in Tables XXV and XXVI, Chapter X. The potency of sunlight lies in the enormous intensities of illumination.

For convenience in considering the various possible sources of artificial sunlight—radiation for health and light for vision—the values in Table XXXV have been separated into footcandles and hours in Table XXXVII. As has been emphasized, we found that the product of intensity (footcandles) and time (minutes) is proportional to erythemal effectiveness of a given source and set of conditions for exposures over the range of our studies. This seems to be definite enough for practical purposes over a range of exposure of at least two hours for minimum perceptible erythema. Therefore, this biological action will be produced by values approximating those in the first two columns. For the longer periods, 4 and 8 hours, all that can be claimed is that the total erythema-producing radiation incident upon a surface illuminated to the intensities indicated for the corresponding periods is the same for these cases as for all others in the table.

At present no one knows whether the health-maintaining value is the same for all these conditions and it will require years of research to establish the facts accurately. However, there are forcible reasons for anticipating a relatively greater effectiveness of small quantities of ultraviolet radiation than of excessive quantities. Certainly, data have been presented in preceding chapters which indicate a very low threshold value.

For example, 6-hour daily exposures to 20 footcandles obtained from a tungsten filament at a temperature slightly above that of the present standard 500-watt lamp and enclosed in a bulb of 888 glass, made a definite improvement in chickens suffering from severe rickets. Daily dosages, producing minimum perceptible erythema as is the case of those in Table XXXVII, are more than prophylactic. They are comparable with curative dosages. In dual-purpose lighting we are concerned with aiding in the maintenance of the health of healthy or moderately healthy persons. This task is admittedly an easier one than the cure of illness. For example, chicks have been reared in perfect health by more or less casual exposures close to a 60-watt tungsten filament in a Corex D bulb. Actually, the lamp was installed in a brooder.

Such a view as the foregoing tends to lower the footcandle values in Table XXXVII very materially. For example, authorities have stated that rickets is prevented by no more than one-tenth the dosage required to cure it. From this viewpoint the values in the table could be reduced to one-tenth. This brings the footcandles in all cases well within the range of present lighting practice. In fact, nearly all the values in the table are economically justifiable even for ordinary lighting.

In the case of the quartz mercury arcs with thin filters of the glasses indicated the intensities involved for 4-hour periods are inadequate for ordinary lighting purposes. Tungsten-filament lamps in ordinary bulbs could be added, thereby increasing the footcandles without appreciably increasing the intensity of the biologically-active radiation.

In the case of the low-pressure mercury arcs with long tubes of suitable glass, the intensity in footcandles for the 4-hour period is fairly satisfactory. It can be doubled by using a porcelain enamel reflector without increasing the intensity of biologically-active radiation as seen in the table. On the other hand, if an oxidized aluminum reflector is used, the intensity of visible and also of desirable ultraviolet radiation are approximately doubled.

In general lighting there is a great diversity in the daily use of it. In congested cities there are many places where artificial light is used throughout the day. There are many other places where it should be in use throughout the entire work-period. The average use of artificial lighting in the work-world is in the neighborhood of three hours daily. There is an adequate factor of safety in the adaptability of the human skin to take care of the variation in exposure to artificial lighting as discussed in Chapter V; but doubtless it is better to design the specific installations for proper intensity in footcandles and proper total quantity of erythema-producing radiation. When attention has been properly directed upon the desirability and effectiveness of mild untraviolet, sub-erythemal dosage is likely to be generally approved. Then the maximum exposure—an entire work-period—could be such as to produce minimum perceptible erythema on average untanned skin. For example, 9 footcandles from a Sunlight (Type S-1) lamp in a Corex D bulb for 8 hours, as indicated in Table XXXVII, will be considered to deliver adequate biologically-active radiation even for lesser periods of exposure. But this intensity is too low to satisfy the requirements of vision. Tungsten-filament lamps may be added to increase the intensity of illumination to 30 or 40 footcandles. The expedient of using two different illuminants provides the means of meeting any requirements.

In considering the use of tungsten-filament lamps with special bulbs the intensity of 300 footcandles for the 8-hour period in Table XXXVII appears superficially to be outside the limit of sound economics. However, this value was obtained for a bulb which was far from ideal. It absorbed much of the biologically-active radiation. Furthermore, it appears that far less dosage is effective. For example, if only one-tenth this amount of ultraviolet radiation is effective in health-maintenance, immediately we are confronted with 30 footcandles instead of 300 footcandles. Improvements in bulbs and higher operating temperatures of the filament will greatly increase the available ultraviolet radiation per footcandle. Such a view establishes the tungsten-filament lamp as a practicable possibility.

Certainly, the data in Table XXXVII combined with the data in other chapters and with the foregoing reasoning indicate that there are plenty of promising sources and that the general use of artificial sunlight is economically possible. Whether or not great health-benefits can be adequately proved is not a serious matter. Artificial lighting is essential to our modern indoor living and working. Dual-purpose lighting is merely the addition of biologically-active radiation to the established need of lighting for vision. Eventually, this extended purpose can be realized at little or no cost. The conservation of vision and of other human resources demands much higher intensities of illumination than are now prevalent. In obtaining these, if we design properly with safe illuminants, the health-benefit is more or less a byproduct. Certainly much research is needed to establish accurately the lower limits of intensities of ultraviolet radiation and the details of health-maintenance. However, it is difficult to imagine that there are many persons who do not believe in the direct beneficence of sunlight. This belief should be considerably strengthened by the data and reasoning presented in the foregoing paragraphs and chapters. In artificial sunlight we have complete control of this adjuvant. There are no daily variations and no seasonal failures.

Having had glimpses of the order of magnitude of the intensities and exposures necessary, of the various practicable sources available and of the procedure in designing installations, let us take the final step and consider fixtures and interiors.

Doubtless, many wall-finishes will be developed which will be more or less effective in reflecting the health-maintaining ultraviolet radiation. Where the extravagance is permissible, ceilings can be covered with a suitable metal. Aluminum foil and paints could be utilized with the proper varnishes or lacquers applied thinly. Plaster is an efficient reflector for this purpose. Aluminum powder might be mixed with it for a surface coating. Many other expedients could be utilized if it becomes worth while to obtain high reflectance for ultraviolet radiation. However, the finishes of walls and ceiling need not be modified if the fixtures are so designed that the ultraviolet

radiation is directed generally downward. This downward component alone does not provide the best lighting. An in-

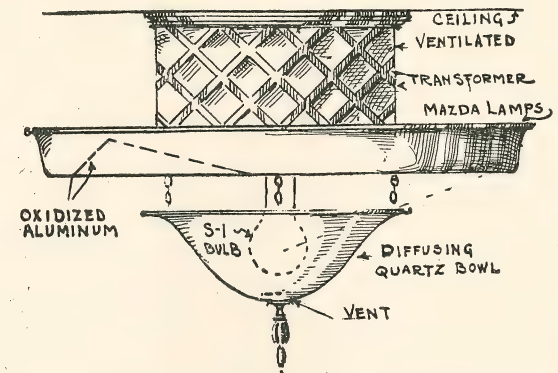

Fig. 56. A dual-purpose lighting fixture with reflector of oxidized aluminum and a pendent bowl of diffusing glass. Tungsten-filament lamps may be concealed above the aluminum reflector. This was designed primarily for the Sunlight (Type S-1) lamp.

direct or upward component may be supplied by means of ordinary tungsten-filament lamps. Of course, in factories

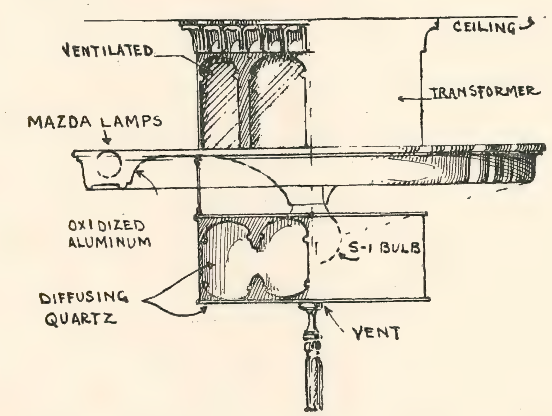

Fig. 57. Another new-era lighting fixture designed to conserve ultraviolet radiation by confining it to the downward component. The upward component is obtained by ordinary tungsten-filament lamps.

where the ceiling cannot be depended upon for reflecting light a direct-lighting system must be used. But even in such a case a

slight percentage of upward light improves the effect by reducing the harshness.

The mercury arcs with their long reflectors are satisfactorily

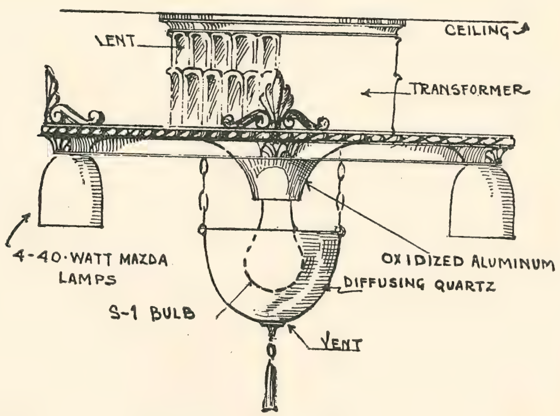

FIG. 58. The source of ultraviolet radiation is concealed in the central pendent shade of diffusing quartz. Four tungsten-filament lamps provide auxiliary lighting.

used in factories. As already indicated, the reflector may be oxidized aluminum or porcelain enamel depending upon whether the amount of ultraviolet radiation is to be increased

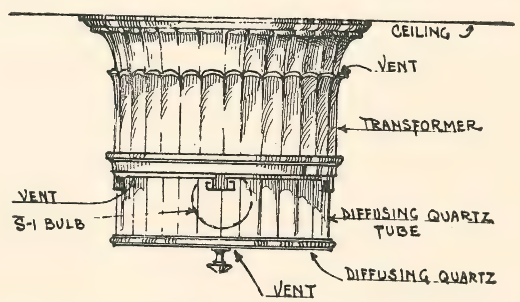

FIG. 59. A fixture utilizing quartz tubing for the sides and a diffusing quartz plate at the bottom. This could house a mercury arc, Type S-1 lamp, or other suitable source.

or not. These reflectors reflect approximately the same amount of light but the porcelain enamel reflects practically no useful ultraviolet radiation. In factories where the ceiling cannot be

depended upon, pendent reflectors containing Sunlight (Type S-1) lamps or even tungsten filaments in special bulbs are simple solutions of dual-purpose lighting. In the case of the Type S-1 lamp, as long as it is a low-voltage lamp, either a special circuit must be provided or provision must be made for housing the transformer in the fixture. With our present wiring systems the latter expedient will usually be more satisfactory. It also may be possible to operate this lamp in series with tungsten-filament lamps of proper design, thereby improving the over-all power-factor and utilizing a more efficient electrical system. These are matters to be solved by experience.

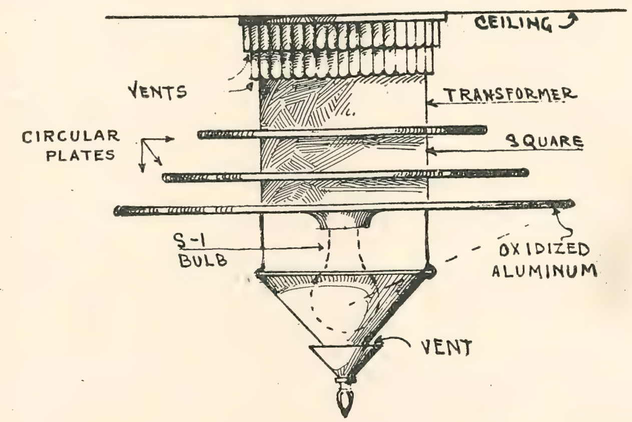

FIG. 60. A modern fixture employing a circular disk of oxidized aluminum for a "ceiling" and conical shades of metal or of dense diffusing quartz.

In interiors, where the ceiling can be utilized for improving the lighting effect, special fixtures can be devised. A few of many possible designs are reproduced herewith. In Fig. 56 a fixture is shown with its own "ceiling" of oxidized aluminum. The source in this case is a Type S-1 lamp but it could be any other suitable one. The source is concealed by a pendent bowl of inexpensive diffusing quartz with a vent in the bottom, if necessary. In the case of the former source a transformer is housed in the upper part of the fixture. An indirect component of light could be obtained from ordinary tungsten-filament lamps concealed above the oxidized aluminum reflector. A

fixture similar in principle but of different appearance is shown in Fig. 57. If the Type S-1 lamp is used, the transformer may be concealed as shown. In Fig. 58 the source of ultraviolet radiation is concealed in the central pendent shade of diffusing quartz. Four ordinary tungsten-filament lamps provide auxiliary lighting.

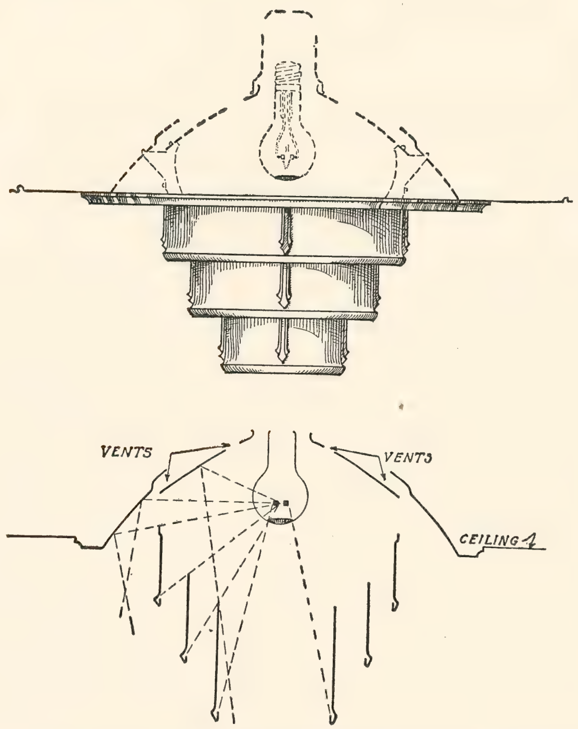

Fig. 61. A fixture designed for dual-purpose light and ultraviolet radiation in a large room. The cylinders of oxidized aluminum are carefully designed so that the source is concealed.

A unique application of quartz tubing is suggested in Fig. 59. The bottom is covered with a plate of diffusing quartz. Such a fixture could house a mercury arc, a Type S-1 lamp, a tungsten-filament lamp in a special bulb, or any suitable source of light and ultraviolet radiation. There is space available for a transformer or other mechanism if necessary. Another modern design is illustrated in Fig. 60. The "ceiling" is

the lowest circular plate of oxidized aluminum. The conical shades could be of suitable metal or of dense diffusing quartz.

In all these cases any suitable ultraviolet-transmitting glass

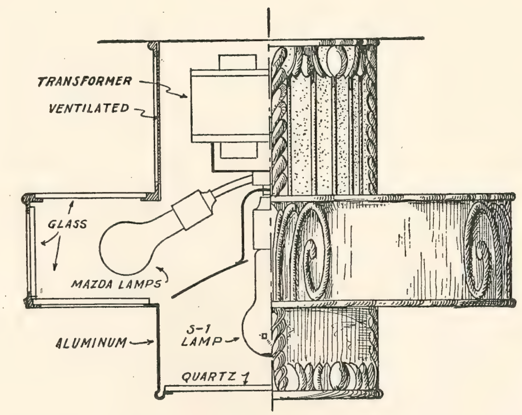

Fig. 62. A de luxe fixture for offices employing a source of light and ultraviolet radiation for the downward component and ordinary tungsten-filament lamps for auxiliary lighting.

may be substituted for the quartz. However, at the present time there is no glass which efficiently transmits radiation from λ2800 to λ3100 when of thicknesses usually considered neces-

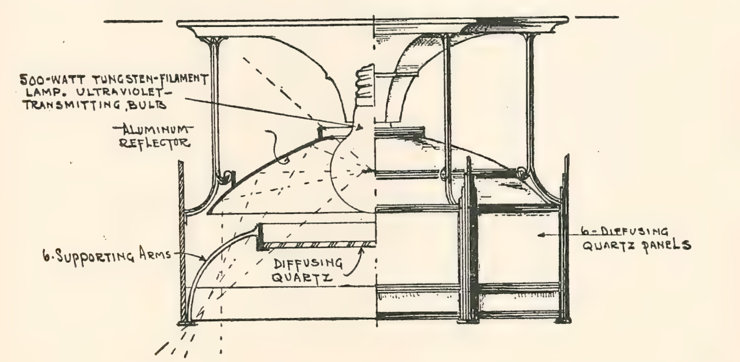

Fig. 63. A design for a 500-watt tungsten-filament lamp equipped with an ultraviolet-transmitting bulb. Materials are aluminum and diffusing quartz which conserve the ultraviolet radiation chiefly in a downward component.

sary for adequate strength of illuminating glassware. Doubtless, such accessories will be developed.

Fig. 61 represents a fixture which was designed for a large room. The cylinders of aluminum are of proper size and location so that the source is shaded. When the Type S-1 lamp is used the pool of mercury in the bottom of the bulb obscures the source from below. These units were also supplemented by several fixtures containing tungsten-filament lamps.

In Fig. 62 is illustrated a de luxe office fixture combining a Type S-1 lamp with ordinary tungsten-filament lamps. Provision has been made for housing the transformer and for confining the ultraviolet radiation to the downward component. Fig. 63 illustrates a fixture designed for conserving the ultraviolet radiation from a 500-watt tungsten-filament lamp in a special bulb. A small amount of light escapes upward.

These are a few suggestions which indicate that the design of fixtures offers no insurmountable difficulties. In fact, as dual-purpose lighting develops, more materials should become available so that the new-era fixtures can be designed with as much ease and freedom as ordinary lighting fixtures.

In this treatise of dual-purpose lighting the discussion has been confined entirely to the aspect of radiation for health-maintenance. This is the added feature which makes dual-purpose lighting. It is understood that all the established principles of adequate and proper lighting for vision are to be adhered to as far as possible in extending the purpose of lighting. Adequate intensities of illumination, shaded light-sources, diffused light, proper direction and quality still remain of great importance.

In closing, let us view natural lighting indoors. The quality and quantity of outdoor daylight remain the ideals toward which we continue to strive in providing artificial light for serious visual tasks. For health-maintenance we must also be guided more or less by these same factors of direct sunlight. Indoors our considerations must be modified by conditions peculiar to this artificial world. Intensities of illumination are much less indoors than outdoors; therefore, as already indicated, the health-maintaining radiation in artificial sunlight must be present in far greater amounts per footcandle than in direct sunlight. This and other factors have been taken into account in our researches and the erythema-footcandle basis provides suitable data.

Naturally, in artificial lighting cost has had more than its share of consideration. Daylight has carelessly been accepted without considering the cost. Long ago we made a study of the cost of daylight [45] and found that indoors it was comparable with that of artificial lighting for the single purpose of seeing. Since then a colleague, L. L. Holladay,[46] made an extensive investigation of the cost of lighting industrial buildings with natural and artificial light. The work was not begun with any idea of eliminating natural light from our interiors. Certainly we want windows where they are advisable if for no other reason than to "let vision out." Our studies were begun in order that we might have a view of the cost data for it was obvious that architects and others were suffering from the daylight habit. Artificial light had become adequate, controllable, and inexpensive while habits of centuries had blinded most persons to the great change which had taken place in the past score of years of light-production and lighting development.

In our congested cities, light-courts and set-backs of upper stories add an enormous cost to natural lighting in a futile attempt to obtain adequate daylight into interiors. School buildings are built under antiquated laws with certain window areas which often are handicaps to architectural beauty without accomplishing the desired purpose very well.

Industrial buildings are often confined to one floor with costly roof construction which cannot be justified by a comparison of artificial and natural light on a basis of cost and satisfactoriness. Windows are placed in the upper stories of department stores, wasting display and shelf room and artificial lighting must be operated all day long. The waste of ground area, cubical content, rental areas, the heat-losses, the cost of maintenance, and other factors are endured with little result in lighting. In all these interiors artificial lighting must be provided and maintained against the possible momentary and certain daily failure of natural lighting. On such a basis

artificial lighting is often of much less cost than natural lighting. It can be more satisfactory because of its controllability in quality and quantity of light. And it rarely fails.

If artificial lighting for seeing can compare favorably with natural lighting on a cost basis, it is easily the peer in dual-

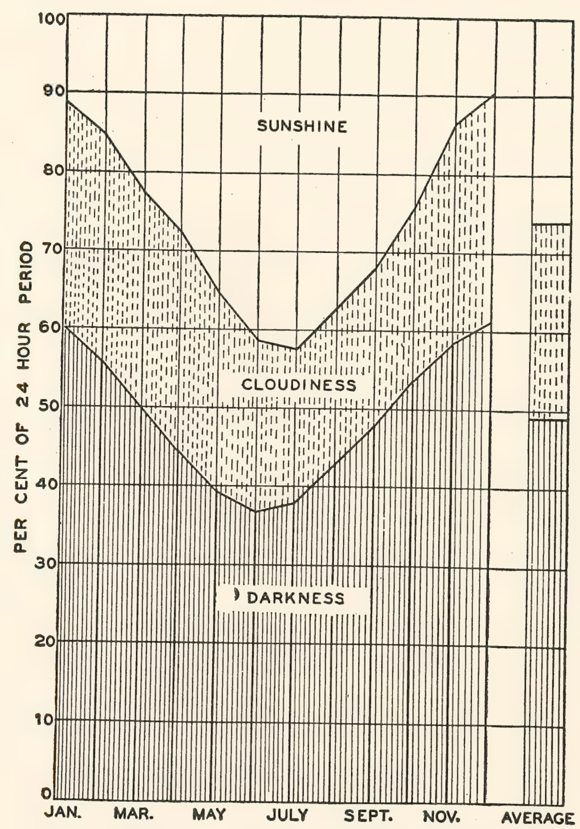

FIG. 64. Average sunshine, cloudiness, and darkness throughout the months of the year in this country.

purpose lighting. It has been adequately proved that sunlight loses its health-maintaining value when filtered through glass. To be beneficial to health, special glass must be used and, if the indoor being is unable to find a place in the sun, large quantities of skylight must be available. The latter is an impossibility in most indoor places. Smoke and haze in cities rob sunlight

of much of its value and throughout the winter months its health-maintaining potency almost entirely disappears even during midday. Therefore, in general lighting indoors natural sunlight can scarcely be compared with artificial sunlight. It is not available during the season when it is most desired. It is available, during the hours when it is potent, only on the top floor or in rooms of southern exposure. In fact, considering the need of special glass for windows and skylights and the limited hours and seasons when it is potent, natural sunlight is not worth considering indoors excepting in special cases.

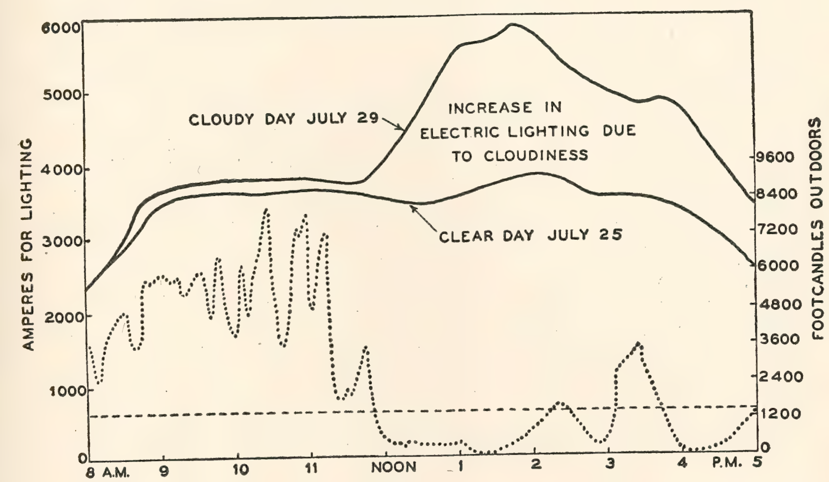

FIG. 65. Illustrating the effect of cloudiness upon indoor artificial lighting. When the intensity of illumination outdoors (dotted curve) drops below 1400 footcandles artificial lighting increases indoors.

The availability of direct sunlight outdoors is indicated in Fig. 64 which is a fair average for this country. In studying this diagram one should bear in mind the lack of biologically-active radiation during the winter months. In this connection, Fig. 5 should be consulted bearing in mind that it represents the maximal values of solar energy shorter than $\lambda 3100$ for a clear, dry atmosphere.

The availability of natural light indoors is well illustrated by Fig. 65. The dotted curve represents the intensity of illumination as measured outdoors by Smirnoff[47] on a more or

less cloudy July 29. About noon the sky became completely clouded. The upper curve indicates that artificial lighting indoors increased when the outdoor intensity decreased to 1500 footcandles or lower. This is proved by comparing the readings of the ammeter in the electric service station on July 29 with those on a typical clear day. By experience we know that the average intensity of natural lighting indoors is about 10 footcandles and about 2 footcandles when it is 1500 footcandles outdoors. Natural sunlight must depend upon high intensities of illumination to be valuable in health maintenance. These are not available indoors excepting through large areas of roof skylight or in the direct sunlight of a south window during the midday hours when sunlight contains health-maintaining radiation in adequate quantities.

Thus, it is seen that artificial sunlight can be more than a safe and unfailing substitute for midday midsummer sunlight during the entire year. It provides this indoors where potent sunlight can seldom be obtained. Here again, artificial lighting not only successfully challenges the sun and makes the indoor world independent of it, but it is very much more practicable. As to cost, it is a very small part of the cost of production or of living. Adequate natural sunlight for health as well as for vision cannot be obtained in most of our indoor world at any cost.

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The foregoing are references alluded to in this treatise. In no sense is it to be considered a bibliography. In fact, there is no bibliography of the primary subject which the author has treated, for the viewpoint is too new. A few books which can be recommended for rounding out a view of radiation for health and lighting for vision are:

"Clinical Applications of Sunlight and Artificial Radiation," by Edgar Mayer, Williams and Wilkins, Baltimore.

"Light and Work," by M. Luckiesh, D. Van Nostrand Co.

"Ultraviolet Light and Vitamin D in Nutrition," by Katharine Blunt and Ruth Cowan, Univ. Chicago Press.

"Lichtbiologie and Lichttherapie," by Hans Meyer, Urban u. Schwarzenberg, Berlin.

"The Chemical Action of Ultraviolet Rays," by Ellis and Wells, Chemical Catalog Co., Inc.

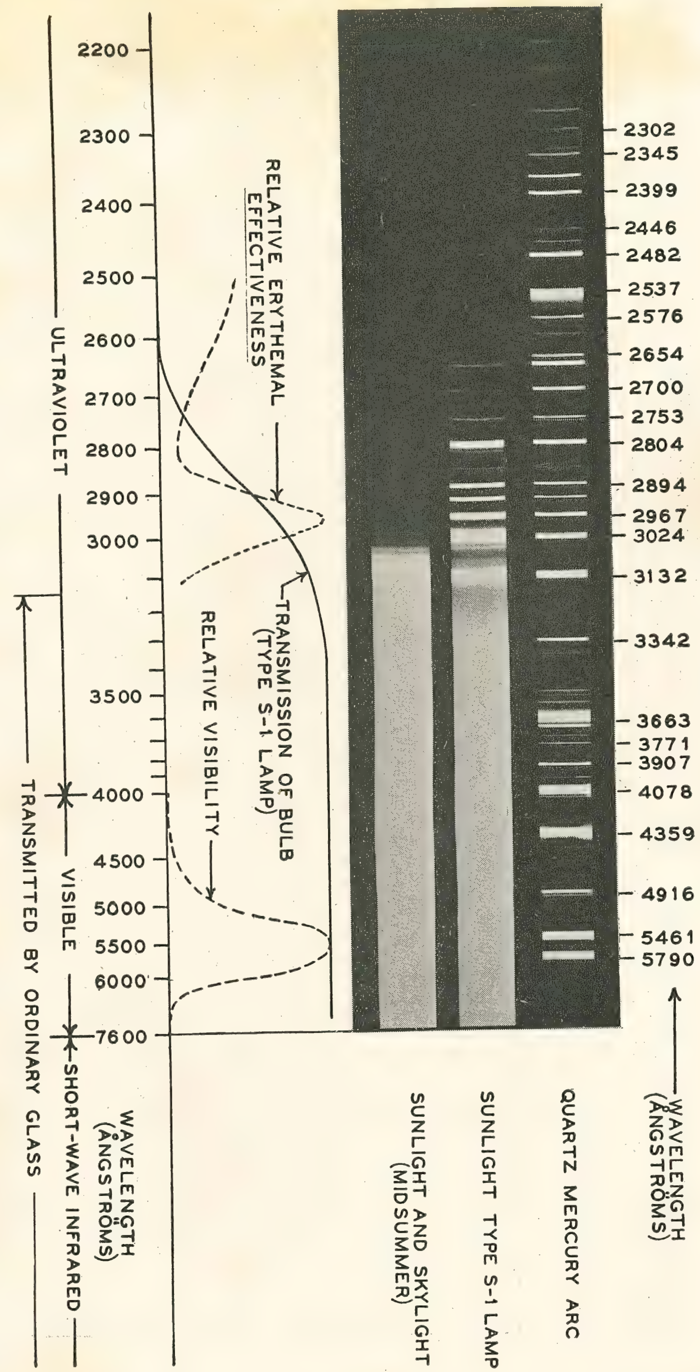

PLATE I The spectrum of midsummer sunlight extends almost to λ2900, but the energy diminishes so rapidly beyond λ3000 that this portion of the spectrogram is lost in reproduction. The spectra of radiation from the quartz mercury arc and from the Sunlight (Type S-1) lamp with a thin Corex D bulb are also shown. There are two important spectral regions in artificial sunlight for general use—the biologically-active radiation (chiefly λ2800 to λ3100) and the visible radiation (λ3900 to λ7600).

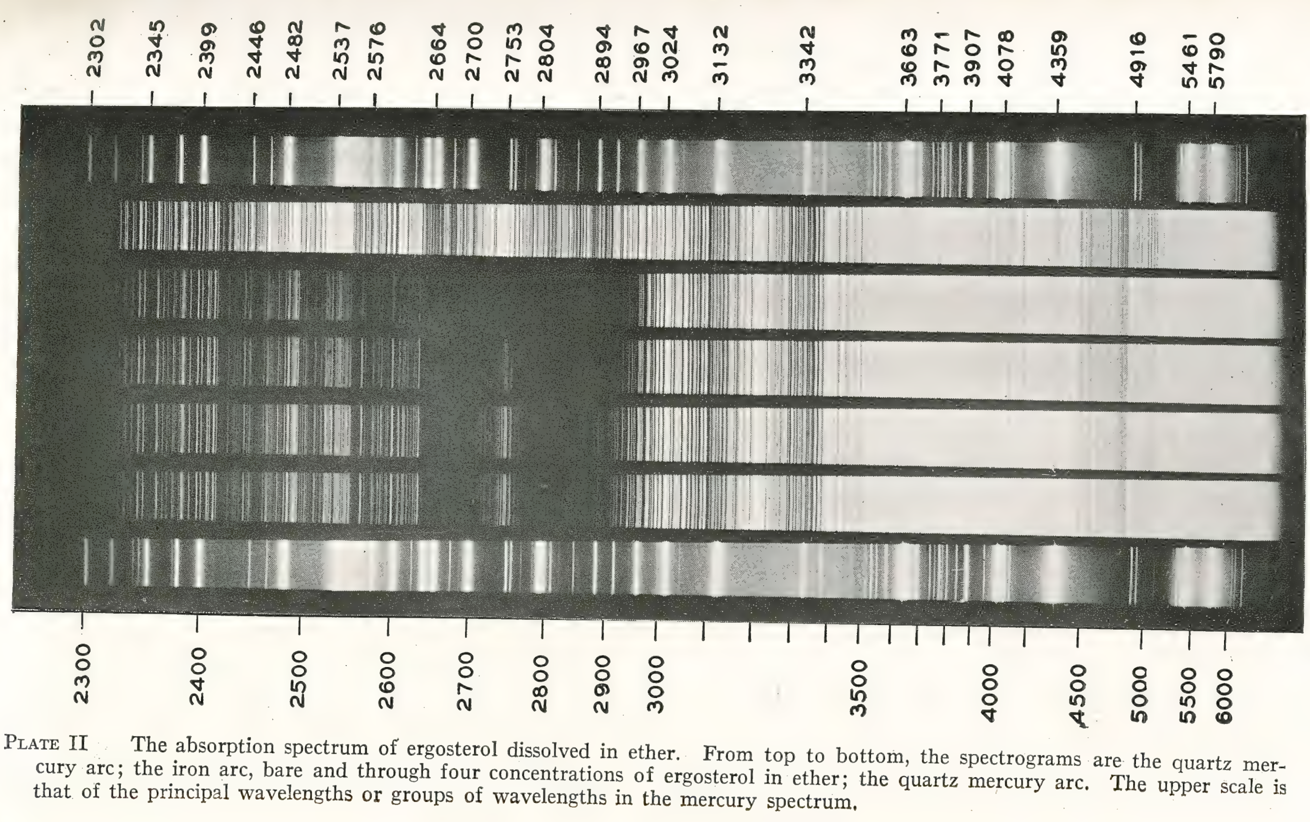

Plate II The absorption spectrum of ergosterol dissolved in ether. From top to bottom, the spectrograms are the quartz mercury arc; the iron arc, bare and through four concentrations of ergosterol in ether; the quartz mercury arc. The upper scale is that of the principal wavelengths or groups of wavelengths in the mercury spectrum.

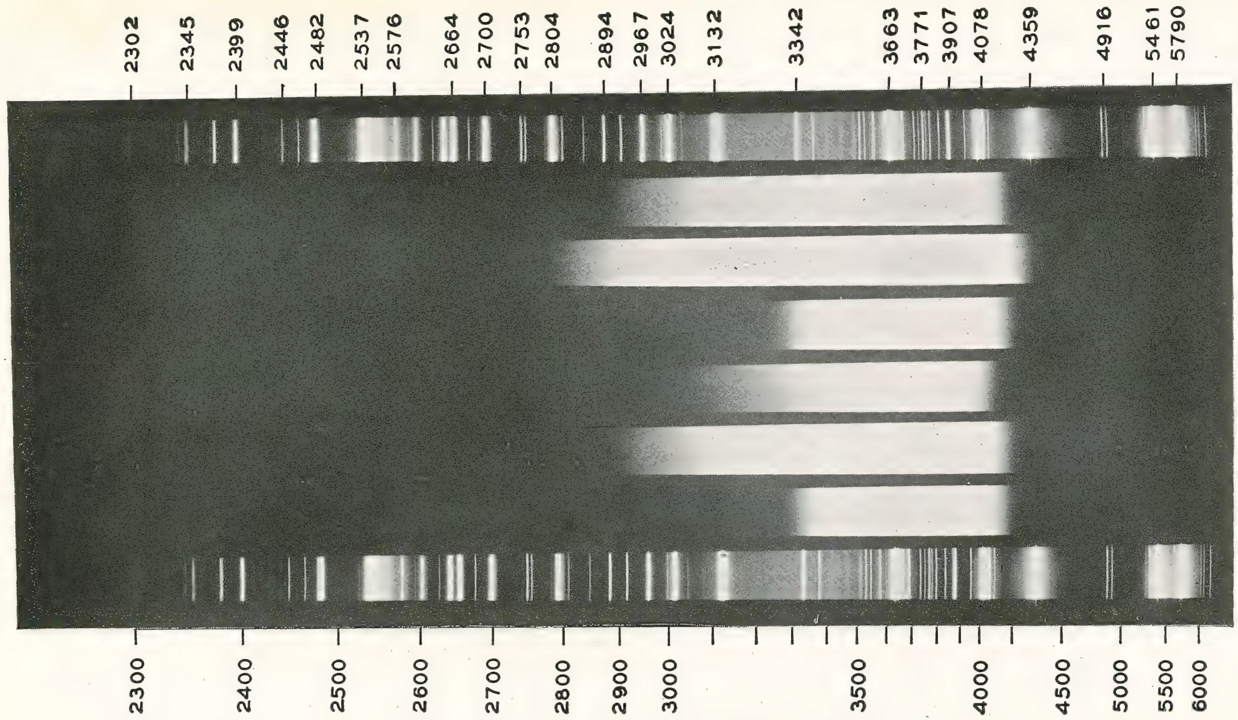

Plate III The ultraviolet spectra of radiation emitted by tungsten filaments obtained with special precautions to eliminate scattered radiation. From top to bottom, the spectrograms are

Quartz mercury arc
500-watt tungsten filament in bulb of 888 glass; exposure 15 min.
Same; exposure 250 min.
Same; with common window-glass interposed; exposure 250 min.
60-watt tungsten filament in Corex D bulb; exposure 15 min.
Same; exposure 250 min.
Same; with common window-glass interposed; exposure 250 min.

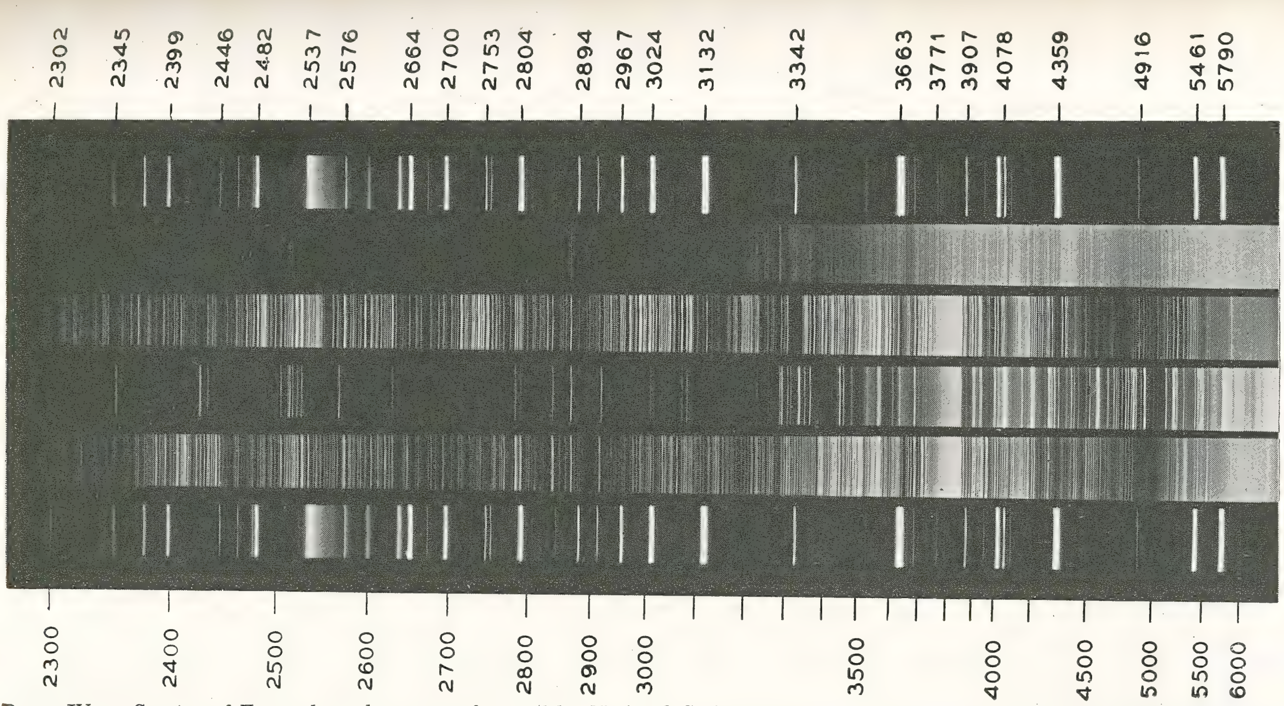

PLATE IV Spectra of Eveready carbons manufactured by National Carbon Company. From top to bottom, the spectrograms are

Quartz mercury arc
Eveready Sunshine carbons
Eveready C carbons
Eveready E carbons
Eveready K carbons
Quartz mercury arc

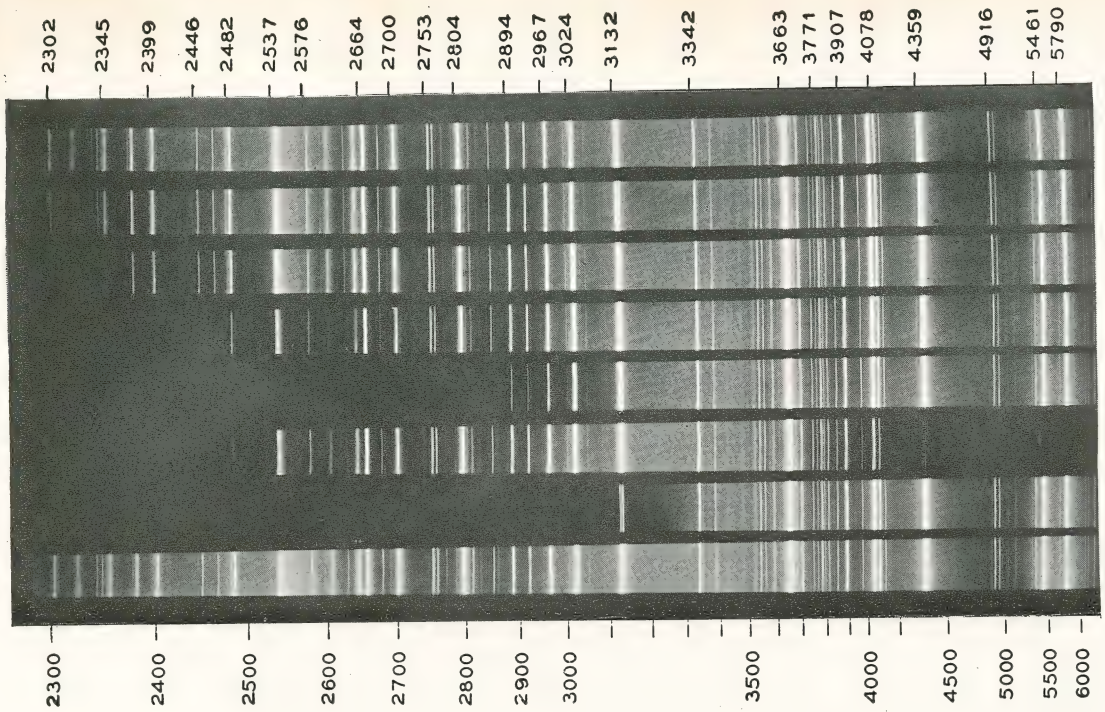

PLATE V Spectra of radiation from a quartz mercury arc through various glasses. From top to bottom, the spectrograms are

Quartz mercury arc
Corex A, 1.94 mm. (thickness)
Corex A, 5.0 mm.
Corex D, 0.5 mm.
Corex D, 5.0 mm.
Red purple (Corning), 4.62 mm.
Blue fluorescing (Corning), 4.0 mm.
Quartz mercury arc

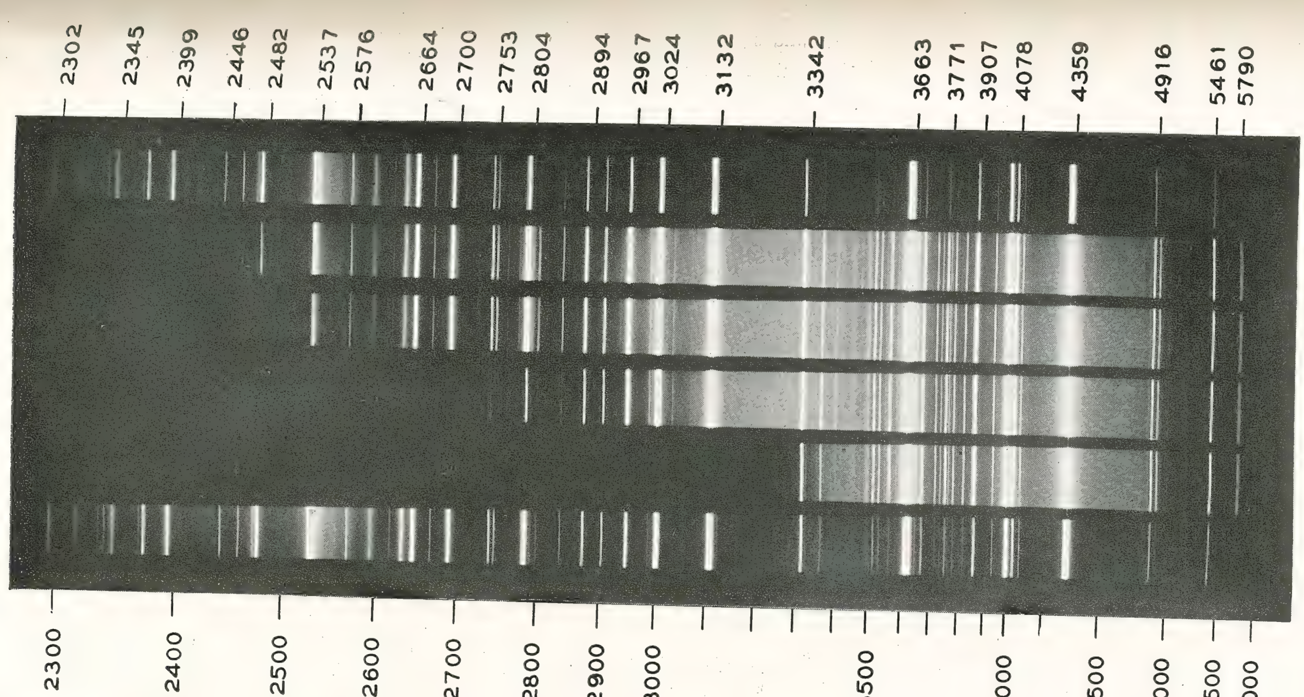

PLATE VI Spectra of radiation from a quartz mercury arc through various glasses. From top to bottom, the spectrograms are

Quartz mercury arc
Corex D, 0.5 mm.
888 glass, 0.7 mm.
690 glass, 1.0 mm.
Common window-glass, 3.0 mm.
Quartz mercury arc

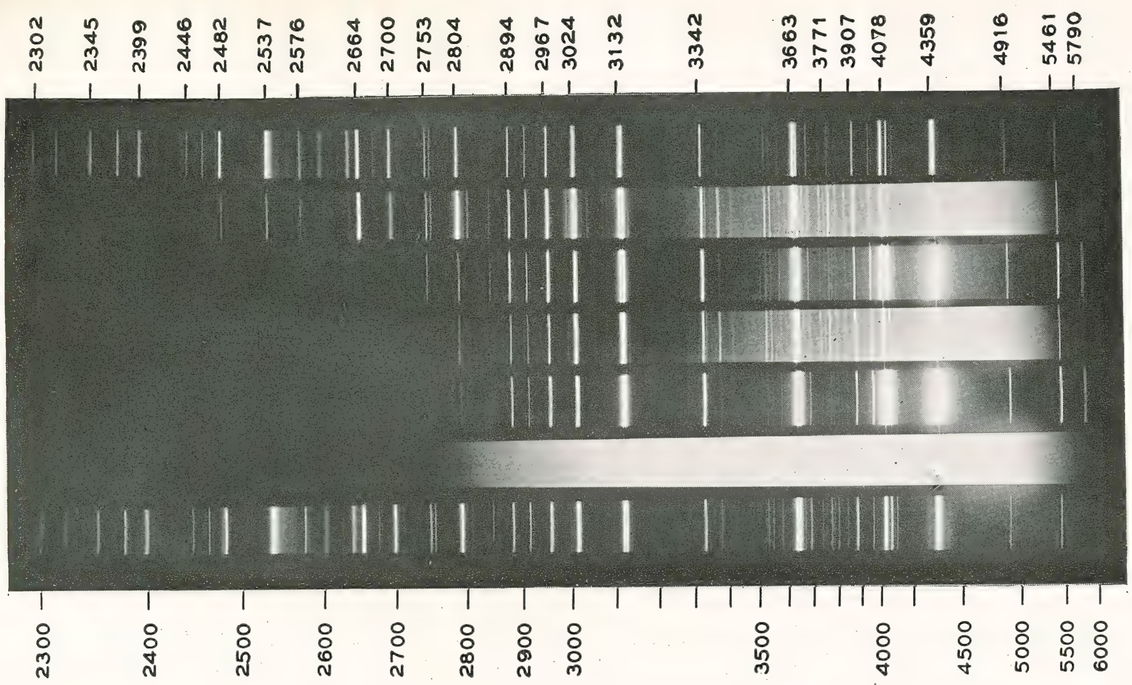

PLATE VII Spectra of radiation from some of the sources studied for erythemal effectiveness. (See Table XXXV.) From top to bottom, the spectrograms are

Uviarc, quartz mercury arc
Sunlight (Type S-1) lamp, thin Corex D bulb
Cooper-Hewitt (low-pressure) mercury arc, 888 glass tube
Sunlight (Type S-1) lamp, 690 glass bulb
Cooper-Hewitt (low-pressure) mercury arc, 690 glass tube
500-watt tungsten filament in 888 glass bulb
Alpine sunlamp, quartz mercury arc

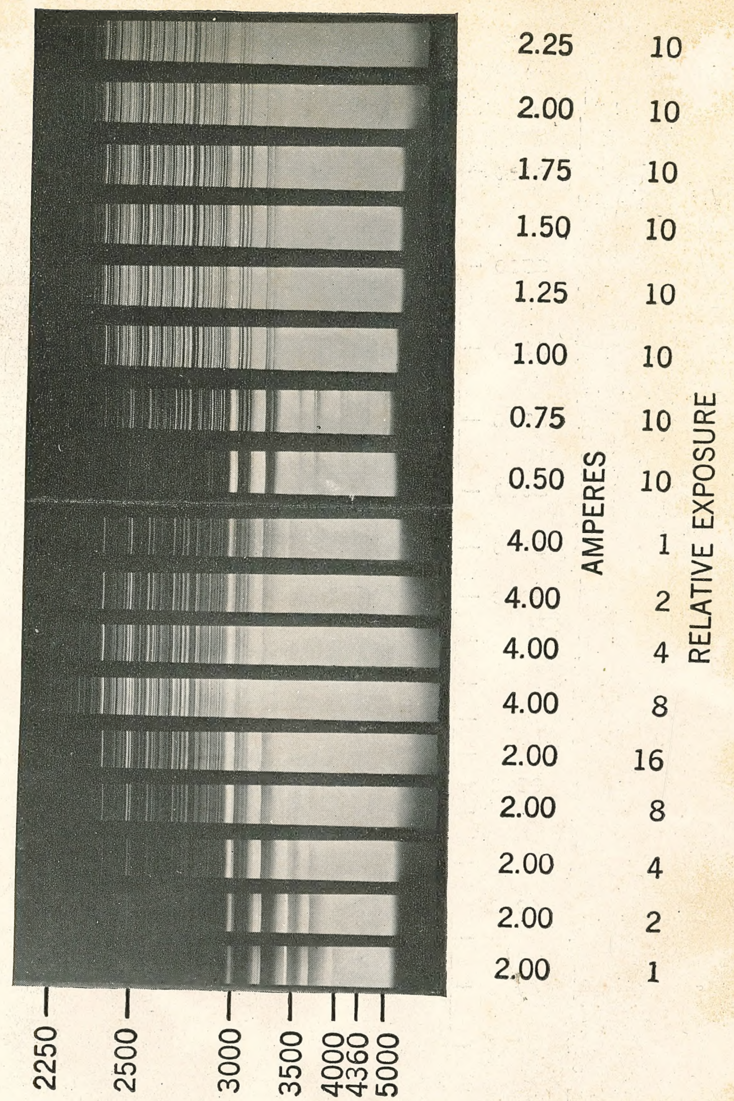

PLATE VIII Ultraviolet spectra of the tungsten arc through quartz, for different amperes and exposures. The current was varied from 0.5 to 4 amperes and the relative photographic exposure from 1 to 16. The upper eight spectrograms are not entirely comparable with the lower nine.

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